GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

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Project No. E-21-H00* GTRI/~~GIT~~ DATE 4 /19 /84

Project Director: Dr. D. T. Paris & Dr. R. W. Schafer School/~~Lab~~ Elect. Engr.

Sponsor: U. S. Army Research Office, Research Triangle Park, NC

Type Agreement: SFRC DAAG29-84-K-0024

Award Period: From 4/15/84 To ~~4/14/86~~ 6-14-87 (Performance) 6/14/85 (Reports)

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Title: Two-Dimensional Signal Processing and Storage and Theory and Applications of Electromagnetic Measurements

ADMINISTRATIVE DATA

OCA Contact William F. Brown X4820

1) Sponsor Technical Contact:

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US Army Research Office
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Research Triangle Park, NC 27709

2) Sponsor Admin/Contractual Matters:

Mr. Thomas A. Bryant
ONR RR
Georgia Tech

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RESTRICTIONS

See Attached Gov't Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT, if specified in the proposal and not otherwise indicated in the short form research contract

COMMENTS:

* All funds (including cost sharing) are budgeted in subprojects identified as follows:

E-21-H01/Schafer	E-21-H04/Rhodes
E-21-H02/Barnwell	E-21-H05/Smith
E-21-H03/Gaylord	E-21-H06/Joy

Note: E-21-H00 is a Follow-on to E-21-F00

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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 10-22-87

Project No. E-21-H00 School/~~Lab~~ EE

Includes Subproject No.(s) E-21-H01, E-21-H02, E-21-H03, E-21-H04, E-21-H05, E21-H06, E21-H07

Project Director(s) D.T. Paris/ R. W. Schafer GTRC/~~GIT~~

Sponsor U. S. Army Research Office, Research Triangle Park, NC

Title Two-Dimensional Signal Processing and Storage and Theory and Applications of Electromagnetic Measurements

Effective Completion Date: 6/14/87 (Performance) 6/14/87 (Reports)

Grant/Contract Closeout Actions Remaining:

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- [x] Final Invoice or Final Fiscal Report
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- [x] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
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Continues Project No. E-21-F00/Paris/ Schafer Continued by Project No.

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FORM OCA 69.285

E-21-H01

ANNUAL REPORT
Joint Services Electronics Program
DAAG29–84–K–0024
April 1, 1984 – December 31, 1984

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

JANUARY 1985

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This is an annual report on research conducted under the auspices of the Joint Services Electronics Program. Specific topics covered are: digital signal processing, parallel processing architectures, two-dimensional optical storage and processing, hybrid optical/digital signal processing, electromagnetic measurements in the time domain, and automatic radiation measurements for near-field and far-field transformations.

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ANNUAL REPORT

Joint Services Electronics Program

Contract DAAG29-84-K-0024

April 1, 1984 - December 31, 1984

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE
AND
THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

January 1, 1985

Georgia Institute of Technology
School of Electrical Engineering
Atlanta, Georgia 30332

TABLE OF CONTENTS

I. OVERVIEW

This annual report covers the first nine months of research carried out under Contract DAAG29-84-K-0024. The research is part of the Joint Services Electronics Program and is administered by the U. S. Army Research Office. Research activities are concentrated in two areas: (1) Two-Dimensional Signal Processing and Storage, and (2) Theory and Application of Electromagnetic Measurements.

The research in two-dimensional signal processing and storage is concentrated in four major areas. These areas overlap and the research activities interact and reinforce one another. Research in Work Unit Number 1, *Multidimensional Digital Signal Processing*, is concerned with the theory, design, and implementation of digital signal representations and digital signal processing algorithms and systems. Work Unit Number 2, *Multiprocessor Architectures for Digital Signal Processing*, focusses upon hardware and software problems in the use of multiport memories and multiple processors for high-speed implementations of digital signal processing algorithms. The research in Work Unit Number 3, *Two-Dimensional Optical Storage and Processing*, is concerned with problems of using holographic information storage as the basis for multiport memories and for optical computation. Work Unit Number 4, *Two-Dimensional Optical/Electronic Signal Processing*, is concerned with the theory, implementation, and application of combined optical and electronic digital signal processing techniques.

The other two work units in the JSEP program are concerned with electromagnetic measurements. In Work Unit Number 5, *Electromagnetic Measurements in the Time- and Frequency-Domains*, research is concerned with both theoretical and experimental investigations of the use of time-domain and frequency-domain methods for measuring the characteristics of materials and electromagnetic systems. Work Unit Number 6, *Automated Measurements for Near- and Far-Field Transformations*, is concerned with assessing the accuracy of computed fields on the surface of lossy radomes and with compensating for probe effects when near-field measurements are made on spherical and arbitrary surfaces.

The report begins with a summary of the most significant accomplishments (in the judgement of the lab directors) during the period April 1, 1984 to December 31, 1984. Following this are brief reports on the individual work units. These reports list personnel supported and discuss in general terms the research that was carried out during the reporting period. Also included in each work unit report is a complete list of publications on the research during this period. Complete copies of these publications are available in the Annual Report Appendix.

III. SIGNIFICANT RESEARCH ACCOMPLISHMENTS

The following accomplishments are, in the judgement of the laboratory directors, of particular significance and potential and are therefore worthy of special mention.

3.1 Optimal Multiprocessor Implementations of DSP Algorithms

The research in Work Unit Number 2 has lead to a new conceptual framework and a new formalism for the description and manipulation of synchronous multiprocessor implementations of highly structured algorithms such as those found in digital signal processing. Earlier work has focussed on a particular architecture termed skewed single instruction multiple data (SSIMD). This earlier research has lead to the discovery of a more general class of multiprocessor implementations that has been called *cyclo-static*. Recent research has shown how to automatically generate rate-optimal, delay-optimal, and processor-optimal cyclo-static realizations for fully specified recursive shift-invariant flow graphs. Cyclo-static implementations have all the advantages of SSIMD implementations with few of the disadvantages. In particular, at least one and often many rate-optimal implementation is always attainable, whereas for SSIMD, a rate-optimal implementation is not always possible. Likewise, at least one rate-optimal, delay-optimal implementation is always attainable. Delay-optimal implementations are seldom attainable for SSIMD. Like SSIMD, cyclo-static implementations are always processor-optimal, and so long as only optimal implementaions are sought, cyclo-static solutions can be found using efficient tree-searching procedures. However, optimal solutions for cyclo-static implementations always exist. Therefore it has been possible to write a program for the automatic generation of cyclo-static solutions from shift-invariant flow graphs. This program is the heart of a "cyclo-static compiler" which can generate control code for a broad class of synchronous MIMD machines.

3.2 New Results in Grating Diffraction Theory

A major achievement of the continuing research of Work Unit Number 3 has been the development of a rigorous coupled-wave theory of grating diffraction. Formerly, this theory was restricted to dielectric materials. Recently, it has been possible to extend the theory to obtain the first unified rigorous (with no approximations) theory of grating diffraction that applies to both dielectric and metallic materials and to planar (slab) and surface-relief structures. As a result of this new theory, it has been shown that a periodic surface on a dielectric can produce zero reflectivity for a given polarization and wavelength. Furthermore, the necessary surface requires only shallow grooves and is insensitive to changes in angle and grating parameters.

3.3 A New Algorithm for Pisarenko Decomposition

A new iterative algorithm has been developed for implementing the Pisarenko decomposition of a signal into a sum of nonharmonically related sinusoids in white noise. The method avoids a difficult eigenvalue computation and contains a built-in criterion for determining the required model order. It is currently being applied to two-dimensional spectrum estimation, spectral line tracking and harmonic decomposition of random processes in non-white noise.

WORK UNIT NUMBER 1

TITLE: Multidimensional Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR: R. W. Schafer, Regents' Professor

SCIENTIFIC PERSONNEL:

M. H. Hayes, Assistant Professor
H. Kobatake, (Visiting Associate Professor)
R. M. Mersereau, Professor
C. Au Yeung, Graduate Research Assistant (Ph.D candidate)
J. E. Bevington, Graduate Research Assistant (Ph.D candidate)
C. C. Davis, Jr., Graduate Research Assistant (Ph.D. candidate)
A. Guessoum, Ph.D. recipient (June 1984)
A. Katsaggelos, Graduate Research Assistant (Ph.D. candidate)
P. Maragos, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to understand the means by which multidimensional signals such as images should be modelled and represented to facilitate the encoding, enhancement, and automatic extraction of information from such signals, and to develop, analyze and extend computer algorithms for these purposes.

RESEARCH ACCOMPLISHMENTS:

A. Fast Algorithms for the Multidimensional Discrete Fourier Transform

This work addressed the problem of designing efficient algorithms for the evaluation of very general multidimensional discrete Fourier transforms defined on arbitrary periodic multidimensional sampling lattices. A new mathematical formulation for the multidimensional DFT was introduced in which the DFT indices were viewed as elements in a lattice which could be manipulated geometrically. A Chinese remainder theorem for integer vectors was then derived which permitted a lattice generalization of the efficient one-dimensional prime factor and Winograd discrete Fourier transform algorithms. A variety of efficient algorithms was developed with careful attention paid to their computational efficiency. Software was developed which has been shared with research groups at Stanford University, North Carolina State University, and the Electromagnetics Group at Georgia Tech.

These results have appeared in the thesis by Guessoum and have been submitted for journal publication.

B. Image Segmentation by Texture

Work has continued on a project in image segmentation by texture. A maximum likelihood detector of the boundary between the two regions of different texture has been discovered and practical simplifications have been made which are partially successful. The resulting detector makes use of 2-D linear prediction residual signals in its classification. We have recognized, however, that this type of classification cannot be performed at the sample (pixel) level; context and global information is important. A framework for encapsulating "higher-level" information, which is updated with various pixel level measurements has been formulated and programmed, but has not yet been extensively tested.

The results on the maximum likelihood boundary detector has been presented at a conference. The other results are still too preliminary.

C. Reconstruction of Multidimensional Signals from Projections

We are looking at the use of iterative signal restoration algorithms applied to the reconstruction of multidimensional signals from projections. This problem has applications in synthetic aperture radar (spotlight mode), computerized tomography, and nondestructive testing. The use of iterative algorithms for this problem is not original although we have proposed some novel variations on these algorithms. The iterative formalism is a useful one since it allows constraints to be placed on the solution. Two new reconstruction algorithms are under study, one of which updates the estimate of the unknown by incorporating information from pairs of projections, and another which works with filtered projections to improve algorithm convergence. These results are not yet ready for publication.

D. Constrained Iterative Signal Restoration

New results in this area have resulted from the application of the regularization method of solving ill-posed problems. Considerable progress has been made toward controlling the effects of noise in image deblurring problems. Progress has also been made in nonstationary image restoration through the development of a technique for incorporating constraints based upon knowledge of human visual perception into the restoration procedure.

E. A Unified Theory of Translation-Invariant Image Processing Systems

The theory of mathematical morphology seeks to quantitatively represent geometrical structure in images. The principles of this theory have been applied to develop a general theory for translation invariant image processing transformations. This theory includes as special cases, median or order-statistics filters and an interesting class of linear systems. Also included is the skeleton transformation, which has been shown to have attractive properties for image coding and the detection of geometric shapes in images.

F. A New Algorithm for Pisarenko Decomposition

A new iterative algorithm has been developed for implementing the Pisarenko decomposition of a signal into a sum of nonharmonically related sinusoids in white noise. The method avoids a difficult eigenvalue computation and contains a built-in criterion for determining the required model order. It is currently being applied to two-dimensional spectrum estimation, spectral line tracking and harmonic decomposition of random processes in non-white noise.

PUBLICATIONS

Theses:

1. A. Guessoum, "Fast Algorithms for the Multidimensional Discrete Fourier Transform," Ph.D. Thesis, Georgia Institute of Technology, June 1984.

Books or Chapters in Books:

1. D. E. Dudgeon and R. M. Mersereau, Multidimensional Digital Signal Processing, Prentice-Hall, Englewood Cliffs, NJ, 1984.

2. M. H. Hayes, "Signal Reconstruction from Spectral Phase or Spectral Magnitude," in Advances in Computer Vision and Image Processing, vol. 1, (T. S. Huang, Ed.) JAI Press, 1984.

Journal Articles (Published or Accepted):

1. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "An Iterative Method for Restoring Noisy Blurred Images," Circuits, Systems, and Signal Processing, vol. 3, no. 2, June 1984.

2. P. A. Maragos, R. W. Schafer, and R. M. Mersereau, "Two-Dimensional Linear Prediction and Its Application to Adaptive Predictive Coding of Images," IEEE Transactions on Acoustics, Speech and Signal Processing, accepted for publication in December 1984.

Papers in Conference Proceedings:

1. D. M. Thomas and M. H. Hayes, "Procedures for Signal Reconstruction from Noisy Phase," Proc. 1984 Int. Conf. on Acoust., Speech and Signal Processing, pp. 31.1.1-31.1.4, March 1984.

2. J. E. Gaby and M. H. Hayes, "Artificial Intelligence Applied to Spectrum Estimation," Proc. 1984 Int. Conf. on Acoust., Speech and Signal Processing, pp. 13.5.1-13.5.4, March 1984.

3. P. A. Maragos, R. M. Mersereau, and R. W. Schafer, "Multichannel Linear Predictive Coding of Color Imaging," Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 29.5.1-29.5.4, March 1984.

4. J. E. Bevington and R. M. Mersereau, "A Maximum Likelihood Approach to Image Segmentation by Texture,' Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 32.7.1-32.7.4, March 1984.

5. P. A. Maragos and R. W. Schafer, "Morphological Skeleton Representation and Coding of Binary Images," Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 29.2.1-29.2.4, March 1984.

6. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "An Iterative Method for Restoring Noisy Blurred Images," Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 37.2.1-37.2.4, March 1984.

7. R. M. Mersereau, "Iterative Algorithms for Deconvolution and Reconstruction of Multidimensional Signals From Their Projections," Nato Advanced Study Institute on Adaptive Methods in Underwater Acoustics.

Papers Submitted:

1. A. Guessoum and R.M. Mersereau, "Fast Algorithms for the Multidimensional Discrete Fourier Transform," submitted to IEEE Trans. Acoustics, Speech and Signal Processing.

2. M. H. Hayes and M. C. Clements, "An Iterative Approach to Pisarenko's Harmonic Decomposition," submitted to IEEE Trans. Acoustics, Speech and Signal Processing.

3. A. Guessoum and R. M. Mersereau, "Fast Algorithms for the Multidimensional Discrete Fourier Transform," submitted to IEEE Trans. Acoustics, Speech and Signal Processing.

4. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, R. W. Schafer, "Nonstationary Iterative Image Restoration," accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

5. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "A General Formulation of Constrained Iterative Restoration Algorithms," accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

6. P. A. Maragos and R. W. Schafer, "A Unification of Linear, Median, Order-Statistics and Morphological Fitlers Under Mathematical Morphology,' accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

7. M. H. Hayes and M. C. Clements, "An Iterative Approach to Pisarenko's Harmonic Decomposition," accepted, 1985 Int. IEEE Conf. on Acoustic, Speech and Signal Processing.

8. A. Guessoum and R.M. Mersereau, "Solution to the Indexing Problem of Multidimensional DFTs on Arbitrary Sampling Lattices," accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

9. M. H. Hayes, M. A. Clements, and D. Mitchell Wilkes, "Iterative Harmonic Decomposition of Nonstationary Random Processes: Theory and Application to Spectral Line Tracking," submitted for publication in Proc. Int. Conf. on Math. in Signal Processing.

WORK UNIT NUMBER 2

TITLE: Multiprocessor Architectures for Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR: T. P. Barnwell, III, Professor

SCIENTIFIC PERSONNEL:

C. J. M. Hodges, Research Engineer
D. A. Schwartz, (Ph.D. candidate)
S. H. Lee, (Ph.D. candidate)
M. J. T. Smith, (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The objective of this research is to develop techniques for the automatic generation of optimal and near-optimal implementations for a large class of Digital Signal Processing (DSP) algorithms on digital machines composed of multiple processors.

RESEARCH ACCOMPLISHMENTS:

This research is centered on the problem of generating highly efficient implementations for a large class of DSP algorithms using multiple programmable processors. This problem is fundamental to many areas of activity, including VLSI design, implementations using arrays of state machines, signal processing chips, or microprocessors, and implementations using networks of general purpose computers.

DSP algorithms are unique in the sense that they usually are both highly structured and highly computationally intense. For this reason, it is often possible to achieve extremely efficient multiprocessor implementations in which the data precedence relations (that is to say the control functions) are maintained through the system synchrony and the system architecture, and every cycle of every arithmetic processor is applied directly to the fundamental operations of the algorithm. The basic goal of this research is to develop automatable techniques for the generation of such synchronous multiprocessor implementations from intrinsically non-parallel algorithm descriptions in such a way that the resulting implementations are both definably and meaningfully optimal. In short, we are developing multiprocessor <u>compilers</u> for DSP algorithms which can be used to generate optimal multiprocessor implementations for both discrete component and VLSI implementations.

Historically, this research has emphasized a set of techniques which we have named <u>Skewed Single Instruction Multiple Data</u>, or SSIMD, realizations. SSIMD implementations are generally realized on synchronous multiprocessors systems composed of many identical programmable processors. In SSIMD implementations, all of the processors execute exactly the same program using a computational mode in which the instruction execution times on the individual processors are skewed. SSIMD implementations have proven to have many desirable properties for DSP implementations. First, since all SSIMD implementations involve only one program, the problem of finding the best multiprocessor implementation reduces to the task of finding the best single processor implementation. Second, given any single processor program suitable for SSIMD implementations, it is possible to compute bounds for the full multiprocessor realization, thereby measuring in very fine grain the quality of the realization. These bounds include the SSIMD sample period bound, which is the minimum achievable time between the processing of input points; the SSIMD delay bound, which is the minimum achievable latency between the arrival on an input and the generation of the corresponding output; and the SSIMD processor bound, which is the minimum number of processors required to achieve the SSIMD sample period bound. Third, and more important, these bounds are not only easily computable, but also easily achievable. In particular, all SSIMD realizations which utilize fewer processors than the processor bound are perfectly efficient (processor optimal) in the sense that an N processor implementation is exactly N time faster than a one processor realization. Finally, the communications architecture required by SSIMD implementations is completely controllable through the specification of the delay (pipeline register) structure within the algorithm itself. For SSIMD realizations, it is always possible to realize the algorithm using a unidirectional nearest neighbor communications structure, but more complex communications architectures can be easily used to advantage if they are available. SSIMD realizations have many advantages for DSP realizations, particularly when compared to such approaches as systolic arrays, wavefront processors, SIMD and general MIMD solutions. In particular, SSIMD solutions tended to be faster, more efficient, and easier to find than the competing techniques. Most of the important results obtained over the past three years have resulted from a systematic attempt to understand the nature of the advantages which seemed to be inherent in the SSIMD approach.

We now know that SSIMD realizations are a special case of a more general class of synchronous multiprocessor implementations which we have named Cyclo-static realizations. The SSIMD results were all derived using a formalism which dealt with programs, that is to say sets of instructions for the control of arithmetic processors. We have now developed a similar formalism which deals not with programs, but with algorithms. In particular, we have introduced a three level formalism which allows for the simultaneous description and manipulation of a very large class of DSP algorithms. The three levels of the formalism -- called the graph theoretic level, the matrix level, and the link-list level -- are all mathematically equivalent formalisms each of which is particularly appropriate to understanding or implementing different parts of the theory. The graph theoretic level is most appropriate for conceptualizing the basic techniques. The matrix level is most appropriate to conceptualizing the associated automation techniques. And the link-list level is most appropriate to the actual computer realizations of the optimization techniques.

The algorithms addressed by this theory are those which can be described using fully-specified shift-invariant flow graphs. These graphs are similar to the more familiar shift-invariant signal flow graphs except that the nodes can contain any operators which can be realized by the processors to be used in the final realization. Given such a flow graph, and given the operation timings for the constituent processor which is to be used in the multiprocessor implementation of the flow graph, it is possible to compute absolute bounds on the multiprocessor realization. In particular, three bounds can be computed. The sample period bound is the smallest sample period at which the algorithm may be implemented. The delay bound is the shortest achievable period between an input and a corresponding output. And the processor bound is the fewest processor which can be used to achieve the sample period bound. These bounds give rise to a very fine-grained definition of optimality. An implementation is rate-optimal if it achieves the sample period bound. An implementation is delay-optimal if it achieves the delay bound. An implementation is processor-optimal if it is either perfectly efficient (factor N speedup) or if it achieves the sample period bound using the number of processors specified by the processor bound.

Last year, the application of our new formalism to the SSIMD approach resulted in the development of an SSIMD compiler for signal flow graphs. This compiler, which can be configured to generate code for a large class of discrete and VLSI multiprocessor machines, is currently configured to generate code for the eight-processor, LSI-11 based multiprocessor which has been designed and implemented as part of this research. This compiler always finds a rate-optimal SSIMD implementation if it exists, and finds the best SSIMD implementation if it does not. Because of the great insight attained in the computation of the bounds, it is fairly simple to find a rate-optimal solution if it exists. It is less efficient to find the best sub-optimal solution if that is what is required. SSIMD realizations are always processor-optimal, often rate-optimal, and seldom delay-optimal.

The application of our new formalism to the systolic approach resulted in a rigorous procedure for transforming shift-invariant flow graphs into systolic realizations. This procedure, which can be fully automated, constitutes a formal procedure for both the generation and the verification of systolic implementations. But more important, this procedure showed very clearly the relationship between SSIMD and systolic implementations. Whereas systolic implementations constituted a full parsing of the algorithm in space, the SSIMD approach constituted a full parsing of the algorithm in time, followed by a mapping of time into space. Both the SSIMD and the systolic approach are limited special cases of synchronous multiprocessor implementations, and both have the virtue that they simplify the problem to the point at which it may be solved. Both have the disadvantage that, in simplifying the problem, they have over-constrained the resulting implementations.

This year, major advances have been made in three areas. The first, and most important, is the area of the automatic generation of rate-optimal, delay-optimal, and processor-optimal cyclo-static realizations for fully specified recursive shift-invariant flow graphs. Cyclo-static implementations have all of the advantages of SSIMD implementations without most of the disadvantages. In particular, at least one (often many) rate optimal implementation is always attainable, whereas for SSIMD a rate-optimal implementation was not always achievable. Likewise, at least one rate-optimal, delay-optimal implementation is always attainable. Delay-optimal implementations are seldom attainable for SSIMD. Like SSIMD, cyclo-static implementations are always processor-optimal. Also like SSIMD, so long as only optimal implementations are sought, cyclo-static solutions can be found using efficient tree-searching procedures. Unlike SSIMD, however, optimal solutions for cyclo-static schedules always exist.

Based on the above results (this is mostly the Ph.D. research of David A. Schwartz), a program for the automatic generation of cyclo-static solutions from shift-invariant flow graphs has been demonstrated. This program is the essential part of a 'cyclo-static compiler' which can generate control code for a broad class of synchronous MIMD machines.

The second area in which results have been attained is the area of more efficient techniques for find sub-optimal SSIMD realizations. One of the outstanding problems with the existing SSIMD compiler is that when no optimal implementation exists, finding the best sub-optimal implementation is a computationally intensive process. The new techniques systematically apply constraints to the search for non-optimal SSIMD solutions so as to dramatically reduce the computational cost. A program to realize the techniques developed has been written. This is largely the Ph.D. research of S. H. Lee.

The final area in which progress has been made is in a new formalism for describing maximally decimated analysis/reconstruction systems based on filter banks. Such systems constitute a class of short-time-frequency representations for signals, and are useful for one and two dimensional frequency domain coding and processing. A major earlier result in this area (1983) was the development of techniques for generation of high-quality filter banks which achieved exact reconstruction in the absence of noise. The new formalism extends these results to a much broader class of systems, as well as pulling together many other published solutions under a single umbrella. This is largely the Ph.D. thesis work of M. J. T. Smith.

PUBLICATIONS:

Theses:

1. M.J.T. Smith, "Exact Reconstruction Analysis/Synthesis Systems and Their Application to Frequency Domain Coding," Ph.D. Thesis, Georgia Institute of Technology, December 1984.

Papers in Conference Proceedings:

1. D. A. Schwartz and T. P. Barnwell III, "A Graph Theoretic Technique for the Generation of Systolic Implementations for Shift-Invariant Flow Graphs," Proc. of the International Conference on Acoustics, Speech and Signal Processing, March 1984.

2. D. A. Schwartz and T. P. Barnwell III, "Increasing the Parallelism of Filters Through Transformation to Block State Variable Form," Proc. of the International Conference on Acoustics, Speech and Signal Processing, March 1984.

3. M.J.T. Smith and T.P. Barnwell, III, "A Procedure for Designing Exact Reconstruction Filter Banks for Tree-Structured Subband Coders," Proc. ICASSP'84, March 1984.

Papers Submitted or Accepted:

1. S. H. Lee, C. J. M. Hodges, and T. P. Barnwell III, "An SSIMD Compiler for the Implementation of Linear Shift-Invariant Flow Graphs," accepted, to appear at Int. Conf. on Acoustics, Speech and Signal Processing.

2. D. A. Schwartz and T. P. Barnwell III, "Cyclo-static Multiprocessor Scheduling for the Optimal Realization of Shift-Invariant Flow Graphs," accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

3. S. H. Lee, C. J. M. Hodges, and T. P. Barnwell III, "An SSIMD Compiler for the Implementation of Linear Shift-Invariant Flow Graphs," accepted, _1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing_.

4. M.J.T. Smith and T.P. Barnwell, III, "A New Formalism for Describing Analysis/Reconstruction Systems Based on Maximally Decimated Filter Banks," accepted, _1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing_.

WORK UNIT NUMBER 3

TITLE: Two-Dimensional Optical Storage and Processing

SENIOR PRINCIPAL INVESTIGATOR: T. K. Gaylord, Professor

SCIENTIFIC PERSONNEL:

M. G. Moharam, Assistant Professor
C. C. Guest, Post Doctoral Fellow
M. M. Mirsalehi, Graduate Research Assistant (Ph.D. candidate)
A. Knoesen, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long-term scientific objective of this research is to develop broadly based, theoretical and experimental knowledge of high-capacity, high-throughput, two-dimensional optical information storage and two-dimensional optical signal processing. This would bring together a range fo concepts from basic physics to signal processing in its most generalized form. An optical digital parallel processor based on truth-table look-up processing implemented in the form of a content-addressable memory would be developed and tested.

RESEARCH ACCOMPLISHMENTS:

A. Residue Number System Truth-Table Look-Up Processing

Truth-table look-up processing using binary coded residue numbers was investigated for full-precision addition and multiplication for implementations using either electronics or optical technologies. The logically minimized numbers of input combinations needed for each operation are presented for moduli 2-23. The moduli sets that require the minimum number of reference patterns are determined for addition and multiplication of 4,8,12, and 16 bit words.

This work showed that the sizes of the truth tables are manageable. A specific procedure for selecting the modulin and minimizing the truth tables was presented. This work was published in the IEEE Transactions on Computers.

B. EXCLUSIVE OR Optical Logic

Theoretical and experimental results were presented for parallel EXCLUSIVE OR processing using thick Fourier holograms. The data pages used contained 1024 bits in a 32 x 32 format. A holographically stored data page is reconstructed together with an input data page that is imaged through the system. The amplitudes of the two wave fronts are adjusted to be equal, and their relative phase is adjusted to be 180°, thus producing the bit-by-bit EXCLUSIVE OR operation between the pages. Using an expanded reference beam for the geometrical configuration treated, it is calculated that the average dynamic range between a 0 and a 1 in the output power would be 17.4 dB. Experimentally, it is shown that excellent EXCLUSIVE OR results are obtainable. An average dynamic range of 7.7 dB was measured, the decrease from the calculated value being primarily due to noise in the video method of detection used in the measurements. The probabilities of miss and false alarm and the total probability of error were also measured. The use of a small diameter reference beam, necessary in some applications, causes a large mismatch in the shapes of the two wave fronts, thus degrading the EXCLUSIVE OR results. It is shown theoretically and experimentally that using an aperture at the recording material produces partial compensation of the wave fronts, thus improving the EXCLUSIVE OR results.

This work was published in Applied Optics.

C. Multi-Level Coding for Residue Number System Truth-Table Look-Up Processing.

The effect of coding level on the number of required reference patterns in a residue-based content-addressable-memory (CAM) has been examined. For moduli expressable as $M=p^n$, where p is a prime number and n is a positive integer greater than one, use of p-level coding reduces the number of reference patterns to be stored relative to other coding levels. In general, the prime factors that divide a modulus can be used to find the coding level that corresponds to the minimum number of reference patterns. An optical implementation of multi-level coded CAM has been introduced. The minimization of minterms in multiple-valued logic has been briefly discussed and the optical methods of achieving different types of reduced terms have been presented.

This work will be presented at the Optical Computing Conference in March 1985.

D. Unified Theory of Grating Diffraction

The first unified rigorous (without approximations) theory of grating diffraction that applied to 1) dielectric and metallic materials, and to 2) planar (slab) and surface-relief structures has been developed by us. Parts of this work have been published previously. This new unified rigorous coupled-wave analysis will be recognized quickly since our past work restricted to dielectric materials is widely known and accepted.

This work has not yet been published.

E. Antireflection Properties of Dielectric Gratings

It has been shown that a periodic surface on dielectric can produce zero reflectivity for a given polarization and wavelength. Further, the necessary surface requires only shallow grooves and is insensitive to changes in angle and grating parameters.

This is being investigated at the present time.

PUBLICATIONS:

Journal Articles:

1. T.K. Gaylord, and C. C. Guest, "Optical Interferometric Liquid Gate Plate Positioner," Review of Scientific Instruments, vol. 55, pp. 866-868, June 1984.

2. C. C. Guest, M. M. Mirsalehi, and T. K. Gaylord, "Residue Number System Truth-Table Look-Up Processing: Moduli Selection and Logical Minimization," IEEE Transactions on Computers, vol. C-33, pp. 927-931, October 1984.

3. M. G. Moharam, T. K. Gaylord, G. T. Sincerbox, H. Werlich, and B. Yung, "Diffraction Characteristics of Photoresist Surface-Relief Gratings," Applied Optics, vol. 23, pp. 3214-3220, September 15, 1984.

4. C. C. Guest, M. M. Mirsalehi, and T. K. Gaylord, "EXCLUSIVE OR Processing (binary image subtraction) using Thick Fourier Holograms," Applied Optics, vol. 23, pp. 3444-3454, October 1, 1984.

Journal Papers Submitted or Accepted:

1. T. K. Gaylord, and M. G. Moharam, "Analysis and Applications of Optical Diffraction by Gratings," Proceedings of the IEEE, vol. 73, pp. xxx-xxx, 1985. (invited)

2. T. K. Gaylord, M. M. Mirsalehi, and C. C. Guest, "Optical Digital Truth-Table Look-Up Processing," Optical Engineering, vol. 24, pp. xx-xx, January/February, 1985. (invited)

3. M. M. Mirsalehi, and T. K. Gaylord, "Comments on Direct Implementation of Discrete and Residue-Based Functions Via Optimal Encoding: A Programmable Array Logic Approach," IEEE Transactions on Computers, vol. C-33, pp. xxx-xxx, 1984. (submitted)

INTERACTIONS AND TECHNOLOGY TRANSFER:

The rigorous coupled-wave analysis of grating diffraction as developed by us has been adopted by Kaiser Optical for the design of the holographic head-up display in the F-15 fighter aircraft.

WORK UNIT NUMBER 4

TITLE: Two-Dimensional Optical/Electronic Signal Processing

SENIOR PRINCIPAL INVESTIGATOR: W.T. Rhodes, Professor

SCIENTIFIC PERSONNEL:

J.N. Mait, Graduate Research Assistant (Ph.D. candidate)
R.W. Stroud, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to gain a good understanding of the capabilities and limitations of hybrid optical/electronic methods for high throughput processing of 2-D signal information and to develop new and widely applicable techniques based on such methods. Emphasis is placed on establishing the capabilities of systems that mate well with digital signal processing systems.

RESEARCH ACCOMPLISHMENTS:

A. Bipolar Incoherent Spatial Filtering

Our original objective in this area was to develop effective methods for bipolar spatial filtering using incoherent optical systems that are simple to implement and efficient with respect to light utilization. That objective was augmented with the additional goal of maximizing overall system dynamic range in the case where optical and digital subsystems are combined with a scanning operation in between.

Work the past year has seen completion of an elegant unifying theory of pupil function specification for the two kinds of two-pupil hybrid optical/electronic spatial filtering methods (one method involving interference of light from the two pupils, the other method not). Further, a two-step algorithm has been developed for designing pupil functions that are optimal in the sense of reducing noise and enhancing contrast. In this work suitable point and global performance measures for noise and contrast have been developed. The pupil function design algorithms, which are based on constrained iterative methods currently of considerable interest in the digital image restoration community, were tested to verify that the optimal pupil functions provide a measureable improvement over nonoptimal pupil functions. A doctoral dissertation on this work should be completed by January 1985. Manuscripts for publication will be submitted shortly thereafter.

B. Opto-Electronic Processor Architectures

Work during the past year has emphasized the development and comparison of different architectures, based on multi-transducer acoust-optic device technology, for highspeed matrix-vector and matrix-matrix processing. Two concerns have received particular attention: (1) fundamental limitations on processor capabilities and (2) increasing processor accuracy through quasi-digital methods. Developments in both areas are reported in a recent invited paper in the Proceedings of the IEEE.

Algebraic optical processing has received considerable attention at a number of research organizations during the past two to three years, and several resonably large contracts are currently being funded by DOD laboratories for the construction of opto-electronic matrix-vector processors. Unfortunately, our studies, as well as those of others, indicate that the digital accuracy opto-electronic processors that can be constructed on the basis of current ideas will have no significant speed advantage over all-electronic counterparts (weight and power consumption might be better). As a consequence, we plan a shift in emphasis under this sub-area away from acousto-optic device technology and the DMAC (digital multiplication by analog convolution) approach for achieving digital accuracy. We plan to place greater emphasis on investigating the potential of arrays of bistable opto-electronic devices for algebraic and two-dimensional signal processing.

PUBLICATIONS:

Journal Articles:

1. William T. Rhodes and Peter S. Guilfoyle, "Acousto-Optic Algebraic Processing Architectures," Proceedings of the IEEE, Vol. 72, No. 7, July 1984 (special issue on Optical Computing), pp. 820-830 (invited).

Papers in Conference Proceedings:

1. H. John Caulfield and William T. Rhodes, "Optical Algebraic Processing Architectures and Algorithms," in Optical Computing, John A. Neff, ed. (SPIE, Vol. 456, Jan. 1984) (invited).

Papers at Conferences without Proceedings:

1. Joseph N. Mait, "Optimal Design of Pupil Functions for Bipolar Incoherent Spatial Filtering," presented at the 1984 Annual Meeting of the Optical Society of America, San Diego, October 1984.

Papers Submitted:

1. William T. Rhodes and M. Koizumi, "Complementary Source and Pupil Distributions for Image Enhancement," submitted for publication.

2. William T. Rhodes, Keith D. Ruehle, and Robert W. Stroud, "Two-Dimensional Optical Fourier Transform Holography by Time-Integration Method," submitted for publication.

INTERACTIONS WITH DOD LABS:

Visited U.S. Army Engineer Topographic Laboratory in April 1984 for discussions with Dr. M. McDonnel and Dr. R. Leighty.

Visited Naval Research Laboratory in April 1984 for discussions with Dr. R. Athale and Dr. H. Szu in the Optical Sciences Division.

A private company, Quantum Diagnostics, Inc., on Long Island, is currently constructing an ultra-high-quality optical/electronic system for bipolar incoherent spatial filtering that is based on concepts developed under this Work Unit. According to discussions with their research director the system is intended for commercial rather than military applications. However, their success with the system will have clear implications for military uses also.

REFERENCES

1. W.T. Rhodes and P.S. Guilfoyle, "Acoustooptic algebraic processing architectures," Proceedings of the IEEE, vol. 72, pp. 820-830 (1984).

2. D.A.B. Miller et al., "Quantum well optical modulators and Self Electro-optic Effect Devices (SEED's)," paper to be presented at March 1985 Optical Society of America Topical Meeting on Optical Computing.

3. Robert Seymore, GTE Laboratories, private communication, 5 December 1984.

4. Alan Huang, "Parallel algorithms for optical digital computers," in Proceedings of the 10th International Optical Computing Conference, (IEEE Cat. No. 83CH1880-4, 1983), pp. 13-17.

5. K.H. Brenner and A. Huang, "An optical processor based on symbolic substitution," paper to be presented at March 1985 Optical Society of America Topical Meeting on Optical Computing.

6. See, e.g., D. Psaltis and N. Farhat, "A new approach to optical information processing based on the Hopfield model," to appear in Optics Letters.

WORK UNIT NUMBER 5

TITLE: Electromagnetic Measurements in the Time and Frequency Domains

SENIOR PRINCIPAL INVESTIGATOR: G. S. Smith, Professor

SCIENTIFIC PERSONNEL:

J. D. Nordgard, Professor
W. R. Scott, Jr., Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The broad objective of this research is to develop new methodology for making electromagnetic measurements directly in the time domain or over a wide bandwidth in the frequency domain. This research includes the development of the theoretical analyses necessary to support the measurement technqiues. One aspect of the research is the systematic study of radiating structures placed near or embedded in material bodies. In a practical situation the radiator might serve as a diagnostic tool for determining the geometry, composition or electrical constitutive parameters of the body.

RESEARCH ACCOMPLISHMENTS:

The research conducted during the last year was concentrated on the topic "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas." This research involves the study of three separate configurations for measuring the constitutive parameters of a material:

A. the monopole antenna of moderate electrical size

B. the open-circuited coaxial line of general electrical length

C. the monopole antenna of general electrical length.

The research involving configurations A. and B. is complete, and journal articles describing the results are in preparation.

A brief description of the research accomplishments for these two topics follows.

A. <u>Monopole Antenna</u>

A general technique is developed for measuring the electrical constitutive parameters of a material using a monopole (dipole) antenna. A normalized impedance that is only a function of the dimensionless parameter kh (wave number length) is defined for the antenna. The normalized impedance is expressed as a rational function, and the coefficients in this function are determined from a measurement of the impedance in a standard medium.

The impedance measured in a material with unknown constitutive parameters is used with the rational function to form a polynomial in kh. The constitutive parameters of the medium are determined from a root of this polynomial.

The measurement technique was implemented for a rational function of order three. The constitutive parameters of the alcohol 1-butanol and saline solutions were measured over a range of frequencies using the technique with cylindrical and conical monopole antennas. The measured constitutive parameters are in good agreement with those determined by previous investigators.

B. Open-Circuited Coaxial Line

The open-circuited coaxial line of general length is studied in detail as a sample holder for broadband measurements of the dielectric permittivity. The multivalued nature of the inverse function is described in detail. The error that results from passing onto the wrong branch of the inverse function is analyzed; a procedure that can prevent passing onto the wrong branch is developed. Contour graphs are constructed that quantify the effects of these two errors on the measured permittivity.

A time-domain measurement system was constructed, calibrated, and used with an open-circuited sample cell to measure the permittivities of several primary alcohols over the frequency range 50MHz<f<2GHz. The measured relaxation spectra for these alcohols are in good agreement with those determined by previous investigators.

PUBLICATIONS:

Journal Articles:

1. G. S. Smith, "Limitations on the Size of Miniature Electric Field Probes," IEEE Trans. Microwave Theory and Tech., vol. MIT-32, pp. 594-600, June 1984.

Papers at Conferences with Proceedings:

1. G. S. Smith, "Limitations on the Size of Miniature Electric Field Probes-The Smallest Dipoles," 1984 IEEE Antenna and Propagation Society, International Symposium and National Radio Science Meeting (URSI), Boston, MA, June 1984.

2. G. S. Smith and L. C. Shen, "The Circular Loop Antennas in the Presence of a Material Body," (invited paper) XXIst General Assembly of the International Union of Radio Science (URSI), Florence, Italy, August-September 1984.

Papers Submitted:

1. G. S. Smith and J. D. Nordgard, "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas," submitted for publication.

INTERACTION WITH DOD LABS:

During the year a study of an existing buried antenna was carried out for the Air Force (RADC, Griffiss, AFB). The experimental portion of this study made use of measurement techniques and facilities developed at Georgia Tech on the Joint Services Electronics Program.

WORK UNIT NUMBER 6

TITLE: Automated Radiation Measurements for Near- and Far-Field Transformations

SENIOR PRINCIPAL INVESTIGATOR: E.B. Joy, Professor

SCIENTIFIC PERSONNEL:

W.M. Leach, Jr., Professor
G.K. Huddleston, Associate Professor (Resigned July 1984)
J.M. Rowland, Graduate Research Assistant (Ph.D. candidate)
R.E. Wilson, Graduate Research Assistant (Ph.D. candidate)
A.J. Julian, Jr., Graduate Research Assistant (Ph.D. candidate)
Y. Kanai, Graduate Research Assistant (M.S. candidate)

SCIENTIFIC OBJECTIVE:

The long term objective of this research is to understand the near field and far field coupling between antennas in the presence of scatters. Special emphasis is placed on determination of limits of accuracy in the measurement of the fields radiated or scattered by an antenna-under-test by a second antenna and to develop techniques and computer algorithms for compensation of such measurements due to known geometrical or electromagnetic anomalies.

RESEARCH ACCOMPLISHMENTS:

A. Near-Field Cross-Section Measurement Technique

Initial work has been completed on the plane wave scattering description of near-field coupling among three antennas. Antenna number one is viewed as the source of electromagnetic radiation, antenna number two is viewed as a scatterer of electromagnetic energy and the third is viewed as the receiver of electromagnetic radiation. This general formulation can model both bistatic and monostatic radar cross section measurement systems, both in the near-field and far-field. The model is capable of predicting both far-field bistatic and monostatic radar crossections from near-field measurements. The model has been verified for a single plane wave illumination, bistatic measurement. The model has not been verified for the monostatic case and such verification is important as a key assumption (the application of the "Bistatic Theorem" approximation) must be involked for far field prediction. Preliminary results of this effort were reported at the Antenna Measurement Technique Association Symposium in October, 1984.

B. Plane Wave Spectrum Radome Analysis Including Reflections

An existing plane wave spectrum radome analysis computer algorithm was extended to include inner radome reflections. A transmitting formulation was applied to model the antenna within the radome. The antenna is described by its plane wave spectrum and each plane wave is propagated through the radome multilayer wall. This algorithm was extended by the determination of the plane wave reflection coefficients of the radome wall and subsequent calculation of the amplitude, phase, polarization and direction of propagation of the reflected plane wave. The extended algorithm demonstrated the ability to predict reflection lobes (also called flash lobes) due to internal radome reflection. Results of this work was presented at the 17th Electromagnetic Window Symposium in July 1984.

C. Spherical Surface Near Field Measurements Technique Development

Significant results were obtained on the modeling of spherical surface near field measurement technique. First, the near field coupling between two antennas, one (a near field probe) moving over a spherical surface centered on the other, (the antenna-under test) was analyzed in terms of the plane wave spectrum of the two antennas versus the previously published spherical mode description of the two antennas. The resulting analysis showed that the polarization of the near field probe was the major compensation factor and that within certain bounds on the electrical size of the near field probe and the seperation distance between the near field probe and the antenna-under-test, the plane was spectrum of the near-field probe could be ignored. A paper describing the research was submitted for publication in the IEEE Transactions on Antennas and Propagation. Second, an investigation was conducted into the magnitude of the Fourier spectral components of the spherical wave functions in order to arrive at a sampling theorem for spherical near field measurements. It was found that due to the slow band-limiting process (at levels of 60 dB below the peak-spectial value) of the spherical modes, that accurate field expansion in spherical modes required an oversampling by a factor of approximately 4/3 with respect to the previously reported Nyguist rate. This results was presented at the U.R.S.I. National Radio Science Meeting in June 1984. Third, a simple algorithm was developed for the compensation of probe position error in spherical near field measurement systems. Position error in theta and phi are compensated using the non uniform Fourier sampling technique and position error in radius is compensated by assuming the dominate spherical mode radial dependence for each measurement point. Thus if the true position of measurement is known, through the use of an high accuracy position measurement system, probe position errors may be removed through software compensation. Simulated results were also presented at the URSI meeting.

PUBLICATIONS:

Short Course Texts:

1. J. Frank and E.B. Joy, Phased Array Antenna Technology, Technology Service Corporation, 1984.

2. E.B. Joy, A.L. Maffett and J. Frank, Radar Cross-Section Measurement Techniques, Technology Service Corporation, 1984.

Editor of Meeting Proceedings:

1. E.B. Joy (Editor), "Near-Field Antenna Measurement Techniques," 1984 Proceedings of the AMTA/IEEE APS Near Field Antenna Measurement Techniques Workshop, p. 85, Boston, MA, June 29, 1984.

Papers in Conference Proceedings:

1. E.B. Joy and J.B. Rowland, Jr., "Spherical Surface Sampling," Proceedings of the U.R.S.I. National Radio Science Meeting," Boston, MA, June 25-28, 1984.

2. E.B. Joy, "Near-Field Measurement Facilities and Research Uses at Georgia Institute of Technology," Proceedings of the AMTA/IEEE APS Near-Field Antenna Measurement Techniques Workshop, pp. 66-70, Boston, MA, June 29, 1984.

3. E.B. Joy and D.E. Ball, "A Fast Ray Tracing Algorithm for Arbitrary Monotonically - Concave Three-Dimensional Radome Shapes," Proceedings of the Seventeenth Symposium on Electromagnetic Windows, p. 59, Atlanta, GA, July 25-27, 1984.

4. E.B. Joy and H.L. Rappaport, "PWS Radome Analysis Including Reflections," Proceedings of the Seventeenth Symposium on Electromagnetic Windows, p. 57, Atlanta, GA, July 25-27, 1984.

5. M.B. Punnett and E.B. Joy, "A Computer Analysis of the RF Performance of a Ground-Mounted Air-Supported Radome," Proceedings of the Seventeenth Symposium on Electromagnetic Windows, pp. 9-16, Atlanta, GA, July 25-27, 1984.

6. E.B. Joy, "A Near-Field Radar Cross-Section Measurement Technique," Proceedings of the Annual Conference of the Antenna Measurement Techniques Association, p. 2B6-1, San Diego, CA, October 2-4, 1984.

7. L.E. Corey and E.B. Joy, "Hexagonal Sampling in Near Field Measurements," Proceedings of the Annual Conference of the Antenna Measurement Techniques Association, pp. 3A4-1-3A4-16, San Diego, CA, October 2-4, 1984.

8. J.A. Donovan and E.B. Joy, "A Cylindrical Near Field Test Facility for UHF Television Transmitting Antennas," Proceedings of the Annual Conference of the Antenna Measurement Techniques Association, p. 4A3-1, San Diego, CA, October 2-4, 1984.

Papers Submitted:

1. W.M. Leach, Jr., "A Plane-Wave Spectrum Development of the Spherical Surface Near-Field Coupling Equation," submitted to the IEEE Transactions on Antennas and Propagation.

ANNUAL REPORT
Joint Services Electronics Program
DAAG29 - 84 - K - 0024
January 1, 1985 - December 31, 1985

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

JANUARY 1986

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

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ABSTRACT (Continue on reverse if necessary and identify by block number)

This is an annual report on research conducted under the auspices of the Joint Services Electronics Program. Specific topics covered are: digital signal processing, parallel processing architectures, two-dimensional optical storage and processing, hybrid optical/digital signal processing, electromagentic measurements in the time domain, and automatic radiation measurements for near-field and far-field transformations.

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ANNUAL REPORT

Joint Services Electronics Program

Contract DAAG29-84-K-0024

January 1, 1985 - December 31, 1985

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE
AND
THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

January 1, 1986

Georgia Institute of Technology
School of Electrical Engineering
Atlanta, Georgia 30332

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TABLE OF CONTENTS

I. OVERVIEW

This annual report covers the second year of research carried out under Contract DAAG29-84-K-0024. The research is part of the Joint Services Electronics Program and is administered by the U. S. Army Research Office. Research activities are concentrated in two areas: (1) Two-Dimensional Signal Processing and Storage, and (2) Theory and Application of Electromagnetic Measurements.

The research in two-dimensional signal processing and storage is concentrated in five major areas. These areas overlap and the research activities interact and reinforce one another. Research in Work Unit Number 1, *Multidimensional Digital Signal Processing*, is concerned with the theory, design, and implementation of digital signal representations and digital signal processing algorithms and systems. Work Unit Number 2, *Multiprocessor Architectures for Digital Signal Processing*, focusses upon hardware and software problems in the use of multiport memories and multiple processors for high-speed implementations of digital signal processing algorithms. The research in Work Unit Number 3, *Two-Dimensional Optical Storage and Processing*, is concerned with problems of using holographic information storage as the basis for multiport memories and for optical computation. Work Unit Number 4, *Two-Dimensional Optical/Electronic Signal Processing*, is concerned with the theory, implementation, and application of combined optical and electronic digital signal processing techniques. Work Unit Number 5 is directed toward problems in the design of VLSI implementations of digital signal processing systems.

The other two work units in the JSEP program are concerned with electromagnetic measurements. In Work Unit Number 6, *Electromagnetic Measurements in the Time- and Frequency-Domains*, research is concerned with both theoretical and experimental investigations of the use of time-domain and frequency-domain methods for measuring the characteristics of materials and electromagnetic systems. Work Unit Number 7, *Automated Measurements for Near- and Far-Field Transformations*, is concerned with assessing the accuracy of computed fields on the surface of lossy radomes and with compensating for probe effects when near-field measurements are made on spherical and arbitrary surfaces.

The report begins with a summary of the most significant accomplishments (in the judgement of the lab directors) during the period January 1, 1985 to December 31, 1985. Following this are brief reports on the individual work units. These reports list personnel supported and discuss in general terms the research that was carried out during the reporting period. Also included in each work unit report is a complete list of publications on the research during this period. Complete copies of these publications are available in the Annual Report Appendix.

II. SIGNIFICANT RESEARCH ACCOMPLISHMENTS

The following accomplishments are, in the judgement of the laboratory directors, of particular significance and potential and are therefore worthy of special mention.

2.1 Experimental Demonstration of Parallel Logic Operations

A major achievement of the continuing research in Work Unit Number 3 was the experimental demonstration of both parallel EXCLUSIVE OR and parallel NAND logic operations to achieve content addressability and thus digital parallel truth-table look-up processing. This work was published in the invited paper in *Optical Engineering*.

This result provides practical experimental demonstrations of optical digital parallel processing using array logic. It is highly significant since it demonstrates that large scale parallel digital processors can be implemented optically. Potential applications include remote sensing, air traffic control, synthetic aperture radar imaging, missile guidance, and adaptive antenna array beamforming.

2.2 A Unified Theory of Translation-Invariant Image Processing Systems

A major achievement of the research in Work Unit Number 1 is the development of a new theory for representing images and image processing systems. Maragos, in his Ph.D. thesis, has developed a new theory of translation-invariant systems in which both signals and systems are fundamentally represented by sets rather than by functions. This leads to a new theory of signals and systems in which geometric structure is prominent. The theory has already been applied to gain new insight into the properties and implementation of many common image transformations and it potentially can serve as the basis for the design and implementation of new image transformations specifically directed toward enhancing, detecting, and coding of geometric structure in images.

2.3 Monostatic Near-Field Radar Cross-section Measurement

A monostatic near-field radar cross-section measurement of a simple target (a square flat plate) was performed on a planar surface near-field measurement system. The far-field monostatic radar cross-section was correctly determined from the near-field measurements. This demonstration was an important step in the process of developing the monostatic near-field radar cross-section technique. Should this technique become fully developed, the monostatic scattering of large (full scale) targets could be accurately measured. The near-field, intermediate field and far-field scattering properties are determined in one measurement set. Radar ananoloies such as glint can be accurately predicted from these measurements.

WORK UNIT NUMBER 1

TITLE: Multidimensional Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR: R. W. Schafer, Regents' Professor

SCIENTIFIC PERSONNEL:

M. H. Hayes, Assistent Professor
R. M. Mersereau, Professor
C. Au Yeung, Graduate Research Assistant (Ph. D. candidate)
J. E. Bevington, Graduate Research Assistant (Ph. D. candidate)
C. C. Davis, Graduate Research Assistant (Ph. D. candidate)
L. Hertz, Graduate Research Assistant (Ph. D. candidate)
E. Karlsson, Graduate Research Assistant (Ph. D. candidate)
A. K. Katsaggelos, Ph. D. recipient Sept. 1985
P. A. Maragos, Ph. D. recipient, June 1985
D. M. Wilkes, Graduate Research Assistant (Ph. D. candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to understand the means by which multidimensional signals such as images should be modelled and represented to facilitate the encoding, enhancement, and automatic extraction of information from such signals, and to develop, analyze, and extend computer algorithms for these purposes.

PROPOSED RESEARCH:

A. Image Segmentation by Texture

This work has focused on the use of two-dimensional linear prediction coefficients as features characterizing texture in an image. A maximum likelihood detector of the boundary between two textured regions has been found and some simple segmentation procedures based on standard clustering algorithms have been explored. To date our results have been limited by the block sizes involved. If the blocks over which statistics are gathered are too large, performance is limited. If the blocks are too small our algorithms require inordinate time. Research is focused on more intelligent methods for forming blocks, the size of which can vary with content and whose shape can be irregular. Our computational methods have been generalized to deal with these irregularly shaped blocks.

B. Constrained Signal Estimation

The problems of constrained deconvolution and the problem of power spectrum estimation both involve the estimation of an unknown function given measurements of a linear functional based on that function. In this study we have been extending some of the formalism of the power spectrum estimation problem to the problem of estimating a positive signal from blurred observations. Our intent has been to use the resulting techniques for image restoration. Initially we have chosen our restoration to be that feasible solution which has the maximum entropy. Based on an analogous derivation for the power spectrum estimation problem, we have shown that such a signal must satisfy a parametric model whose number of free parameters equals the number of measurements. Algorithms for finding those parameters have been found. Efficient computational procedures have been developed for solving this problem and these results have been prepared for publications. Procedures have been developed for determining whether a feasible solution exists and they have been formulated as a test.

C. Reconstruction of Multidimensional Signals from Projections

We have looked into the use of iterative signal restoration algorithms applied to the reconstruction of multidimensional signals from their projections, a problem which forms the basis for computer-aided tomography and NMR imaging. A new algorithm has been developed which shows promise as a faster converging iterative procedure. This algorithm has been implemented and the simulations confirm our expectations on some synthetic examples.

D. Signal Modeling and Power Spectrum Estimation

This work has focused on the problem of signal modeling and the use of these models in power spectrum estimation. We have considered the problem of modeling a signal as a sum of sinusoids whose frequencies may vary as a function of time. A fast and efficient procedure for estimating the sinusoidal frequencies has been developed and analyzed for nonstationary signals. Although the work so far has been restricted to one-dimensional signals, our efforts are now focused on the extension of this model and algorithm to two-dimensional signals. We have also looked at the problem of modeling a linear time-varying system with an ARMA lattice filter. A new ARMA lattice filter realization has been developed which is fully consistent with the geometrical characteristics of the well-known AR and MA lattice filters, i.e., it is realized in terms of a fully orthogonal lattice basis and it evaluates all ARMA lattice filters of lower order. A new fast RLS algorithm for the evaluation of the ARMA lattice filter coefficients has also been developed.

E. Constrained Iterative Image Restoration

A general formulation has been developed for constrained adaptive and nonadaptive iterative image restoration algorithms. In this formulation, deterministic and/or statistical information about the undistorted image and statistical information about the noise are directly incorporated into the iterative procedure by what we have called "soft constraints." Spatial adaptivity is introduced by a soft constraint operator that incorporates properties of the response of human vision. The resulting image restoration algorithms are general and can be used for any type of linear constraint and distortion operators.

F. Unified Theory of Translation-Invariant Image Processing Systems

The theory of mathematical morphology seeks to quantitatively represent geometrical structure in images and in image transformations. The principles of mathematical morphology have been appied to develop a new general theory for translation invariant image processing systems. The key to this new theory is the representation of signals as sets rather than as functions. With this representation of signals, systems are represented as set transformations. A major new result is that systems also can be represented by sets, in a way that leads to new implementations and new understanding of image processing systems. This theory has been applied to obtain new insight into such classes of systems as morphological filters, rank-order filters, median filters, matched filters for shapes, and an interesting class of linear systems. The theory is potentially the basis for new approaches to the synthesis of image transformations with specific desired properties. Another result of this research is new insight into skeleton transformations of images. The skeleton has been applied to binary image coding, and it is currently being studied as a means for detecting shapes in images.

PUBLICATIONS

Theses:

1. P. A. Maragos, "A Unified Theory of Translation-Invariant Systems with Applications to Morphological Analysis and Coding of Images", Ph. D. Thesis, Georgia Institute of Technology, July 1985.

2. A. K. Katsaggelos, "Constrained Iterative Image Restoration Algorithms", Ph. D. Thesis, Georgia Institute of Technology, August 1985.

Books or Chapters in Books

1. M. H. Hayes, "The Unique Reconstruction of Multidimensional Sequences from Fourier Transform Magnitude or Phase", to appear in *Image Recovery: Theory and Application*, (H. Stark, ed.), Academic Press, 1986.

2. R. M. Mersereau, "Iterative Algorithms for Deconvolution and Reconstruction of Multidimensional Signals from their Projections", pp. 563-579 in *Adaptive Methods in Underwater Acoustics*, (H. G. Urban, ed.) Reidel, 1985.

Journal Articles (published or accepted)

1. A. Guessoum and R. M. Mersereau, "Fast algorithms for the multidimensional discrete Fourier transform", accepted, *IEEE Trans. Acoustics, Speech, Signal Processing*.

2. M. H. Hayes and M. C. Clements, "An efficient algorithm for computing Pisarenko's harmonic decomposition using Levinson's recursion", accepted, *IEEE Trans. Acoustics, Speech, Signal Processing*.

3. P. A. Maragos and R. W. Schafer, "Morphological skeleton representation and coding of binary images," accepted, *IEEE Trans. Acoustics, Speech and Signal Processing*.

Papers in Conference Proceedings

1. C. AuYeung and R. M. Mersereau, "Maximum entropy signal restoration", *19th Asilomar Conf. on Circuits, Systems, and Computers*.

2. A. Guessoum and R. M. Mersereau, "Solution to the indexing problem of multidimensional DFTs on arbitrary sampling lattices", *Proc. 1985 IEEE Int. Conf. Acoustics, Speech, Signal Processing*, pp. 1535-1538.

3. M. H. Hayes, M. A. Clements, and D. M. Wilkes, "Iterative harmonic decomposition of nonstationary random processes: theory and application", *Proc. Int. Conf. on Math. in Signal Processing*.

4. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "Non-stationary iterative image restoration", *Proc. 1985 IEEE Int. Conf. Acoustics, Speech, Signal Processing*, pp. 696-699.

5. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "A general formulation of constrained iterative restoration algorithms", *Proc. 1985 IEEE Int. Conf. Acoustics, Speech, Signal Processing*, pp. 700-703.

6. P. A. Maragos and R. W. Schafer, "A unification of linear, median, order-statistics, and morphological filters under mathematical morphology," *Proc. 1985 IEEE Int. Conf. Acoustics, Speech Signal Processing*, pp. 1329-1332.

Papers Submitted:

1. C. AuYeung, R. M. Mersereau, and R. W. Schafer, "Maximum entropy deconvolution", *1986 IEEE Int. Conf. Acoustics, Speech, Signal Processing.*

2. E. Karlsson and M. H. Hayes, "Modeling of time-varying systems with ARMA lattice filters", *1986 IEEE Int. Conf. Acoustics, Speech, Signal Processing.*

3. D. M. Wilkes and M. H. Hayes, "Spectral line tracking for nonstationary random processes", *1986 IEEE Int. Conf. Acoustics, Speech, Signal Processing.*

4. P. A. Maragos and R. W. Schafer, "Application of Morphological filtering to image processing and analysis," *1986 IEEE Int. Conf. Acoustics, Speech and Signal Processing.*

5. E. Karlsson and M. H. Hayes, "ARMA modeling of linear time-varying systems: Lattice filter structures and fast RLS algorithms", *IEEE Trans. on Acoustics, Speech, Signal Processing.*

WORK UNIT NUMBER 2

TITLE: Multiprocessor Architectures for Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR:

T. P. Barnwell, III, Professor

SCIENTIFIC PERSONNEL:

C. J. M. Hodges, Research Engineer
D. A. Schwartz, (Ph.D. candidate)
S. H. Lee, (Ph.D. candidate)
V. Owei (Ph.D. candidate)

SCIENTIFIC OBJECTIVES:

The objective of this research is to develop techniques for the automatic generation of optimal and near-optimal implementations for a large class of Digital Signal Processing (DSP) algorithms on digital machines composed of multiple processors.

RESEARCH ACCOMPLISHMENTS:

This research is centered on the problem of generating highly efficient implementations for a large class of DSP algorithms using multiple programmable processors. This problem is fundamental to many areas of activity, including VLSI design; implementations using arrays of state machines, signal processing chips, or microprocessors; and implementations using networks of general purpose computers.

DSP algorithms are unique in the sense that they usually are both highly structured and highly computationally intense. For this reason, it is often possible to achieve extremely efficient multiprocessor implementations in which the data precedence relations (that is to say the control functions) are maintained through the system synchrony and the system architecture, and every cycle of every arithmetic processor is applied directly to the fundamental operations of the algorithm. The basic goal of this research is to develop automatic techniques for the generation of such synchronous multiprocessor implementations from intrinsically non-parallel algorithm descriptions in such a way that the resulting implementations are both definably and meaningfully optimal. In short, we are developing multiprocessor compilers for DSP algorithms which can be used to generate optimal multiprocessor implementations for both discrete component and VLSI implementations.

Historically, this research has emphasized a set of techniques which we have named Skewed Single Instruction Multiple Data, or SSIMD, realizations. SSIMD implementations are generally realized on synchronous multiprocessors systems composed of many identical programmable processors. In SSIMD implementations, all of the processors execute exactly the same program using a computational mode in which the instruction execution times on the individual processors are skewed. SSIMD implementations have proven to have many desirable properties for DSP implementations. First, since all SSIMD implementations involve only one program, the problem of finding the best multiprocessor implementation reduces to the task of finding the best single processor implementation. Second, given any single processor program suitable for SSIMD implementations, it is possible to compute bounds for the full multiprocessor realization, thereby measuring in very fine grain the quality of the realization. These bounds include the SSIMD sample period bound, which is the minimum achievable time between the processing of input points; the SSIMD delay bound, which is the minimum achievable latency between the arrival on an input and the generation of the corresponding output; and the SSIMD processor bound, which it the minimum number of processors required to achieve the SSIMD sample period bound. Third, and more important, these bounds are not only easily computable, but also easily achievable. In particular, all SSIMD realizations which utilize less processors than the processor bound are perfectly efficient (processor optimal) in the sense that an N processor implementation is exactly N time faster than a one processor realization. Finally, the communications architecture required by SSIMD implementations is completely controllable through the specification of the delay (pipeline register) structure within the algorithm itself. For SSIMD realizations, it is always possible to realize the algorithm using a unidirectional nearest neighbor communications structure, but more complex communications architectures can be easily used to advantage if they are available. SSIMD realizations have many advantages for DSP realizations, particularly when compared to such approaches as systolic arrays, wavefront processors, SIMD and general MIMD solutions. In particular, SSIMD solutions tended to be faster, more efficient, and easier to find than the competing techniques. Most of the important results obtained over the past three years have resulted from a systematic attempt to understand the nature of the advantages which seemed to be inherent in the SSIMD approach.

We now know that SSIMD realizations are a special case of a more general class of synchronous multiprocessor implementations which we have named Cyclo-static realizations. The SSIMD results were all derived using a formalism which dealt with programs, that is to say sets of instructions for the control of arithmetic processors. We have now developed a similar formalism which deals not with programs, but with algorithms. In particular, we have introduced a three level formalism which allows for the simultaneous description and manipulation of a very large class of DSP algorithms. The three levels of the formalism -- called the graph theoretic level, the matrix level, and the link-list level -- are all mathematically equivalent formalisms each of which is particularly appropriate to understanding or implementing different parts of the theory. The graph theoretic level is most appropriate for conceptualizing the basic techniques. The matrix level is most appropriate to conceptualizing the associated automation techniques. And the link-list level is most appropriate to the actual computer realizations of the optimization techniques.

The algorithms addressed by this theory are those which can be described using fully-specified shift-invariant flow graphs. These graphs are similar to the more familiar shift-invariant signal flow graphs except that the nodes can contain any operators which can be realized by the processors to be used in the final realization. Given such a flow graph, and given the operation timings for the constituent processor which is to be used in the multiprocessor implementation of the flow graph, it is possible to compute absolute bounds on the multiprocessor realization. In particular, three bounds can be computed. The sample period bound is the smallest sample period at which the algorithm may be implemented. The delay bound is the shortest achievable period between an input and a corresponding output. And the processor bound is the fewest processors which can be used to achieve the sample period bound. These bounds give rise to a very fine-grained definition of optimallity. An implementation is rate-optimal if it achieves the sample period bound. An implementation is delay-optimal if it achieves the delay bound. An implementation is processor-optimal if it is either perfectly efficient (factor N speedup) or if it achieves the sample period bound using the number of processors specified by the processor bound.

Two years ago, the application of our new formalism to the SSIMD approach resulted in the development of an SSIMD compiler for signal flow graphs. This compiler, which can be configured to generate code for a large class of discrete and VLSI multiprocessor machines, is currently configured to generate code for the eight-processor, LSI-11 based multiprocessor which has been designed and implemented as part of this research. This compiler always finds a rate-optimal SSIMD implementation if it exists, and finds the best SSIMD implementation if it does not. Because of the great insight attained in the computation of the bounds, it is fairly simple to find a rate-optimal solution if it exists. It is less efficient to find the best sub-optimal solution if that is what is required. SSIMD realizations are always processor-optimal, often rate-optimal, and seldom delay-optimal.

The application of our new formalism to the systolic approach resulted in a rigorous procedure for transforming shift-invariant flow graphs into systolic realizations. This procedure, which can be fully automated, constitutes a formal procedure for both the generation and the verification of systolic implementations. But more important, this procedure showed very clearly the relationship between SSIMD and systolic implementations. Whereas systolic implementations constituted a full parsing of the algorithm in space, the SSIMD approach constituted a full parsing of the algorithm in time, followed by a mapping of time into space. Both the SSIMD and the systolic approach are limited special cases of synchronous multiprocessor implementations, and both have the virtue that they simplify the problem to the point at which it may be solved. Both have the disadvantage that, in simplifying the problem, they have over-constrained the resulting implementations.

Last year and this year, major advances were made two areas. The first, and most important, is the area of the automatic generation of rate-optimal, delay-optimal, and processor-optimal cyclo-static realizations for fully specified recursive shift-invariant flow graphs. Cyclo-static implementations have all of the advantages of SSIMD implementations without most of the disadvantages. In particular, at least one (often many) rate optimal implementation is always attainable, whereas for SSIMD a rate-optimal implementation was not always achievable. Likewise, at least one rate-optimal, delay-optimal implementation is always attainable. Delay-optimal implementations are seldom attainable for SSIMD. Like SSIMD, cyclo-static implementations are always processor-optimal. Also like SSIMD, so long as only optimal implementations are sought, cyclo-static solutions can be found using efficient tree-searching procedures. Unlike SSIMD, however, optimal solutions for cyclo-static schedules always exist.

Based on the above results (this is mostly the Ph.D. research of David A. Schwartz), a program for the automatic generation of cyclo-static solutions from shift-invariant flow graphs has been demonstrated. This program is the essential part of a 'cyclo-static compiler' which can generate control code for a broad class of synchronous MIMD machines. David Schwartz completed his Ph.D. research in June, 1985, and is continuing in the same general area as faculty member.

The second area in which results have been attained is in developing a multiprocessor compiler which operates from a non-parallel algorithm specification, and efficiently generates optimal constrained multiprocessor implementations for synchronous MIMD machines. The compiler is basically composed of four parts. The first part is a graph generator, which uses a serial algorithm specification to generate a generic flow graph with the minimum potential iteration period bound. The second part is a graph transformation which generates a fully specified flow graph with the minimum possible iteration period bound from the generic flow graph. The third and forth parts combine to efficiently find the best SSIMD, PSSIMD, or static PSSIMD under communications constraints imposed by a processor adjacency map. The major advance in this area is the extension of the concept to bounds so that the optimal implementations can be efficiently found even when a full cyclo-static implementation is excluded. The total effect of this work is a compiler in which the user specifies the desired algorithm serially, and the optimal multiprocessor implementation is generated automatically. This is largely the Ph.D. research of S. H. Lee.

Another major development, which is not really part of this research but will impact it greatly in the future, is the funding by DARPA of a DSP supercomputer project based on the principles developed in this research. This multiprocessor system, called the Optimal Synchronous Cyclo-static Array, or OSCAR, will be developed over a five year period, the first two years of which are currently funded. The OSCAR will be the target of all future multiprocessor compiler development.

PUBLICATIONS:

Thesis:

1. D. A. Schwartz, "Synchronous Multiprocessor Realization of Shift-Invariant Flow Graphs," Ph.D. Thesis, Georgia Institute of Technology, June 1985.

Papers in Conference Proceedings:

1. D. A. Schwartz and T. P. Barnwell III, "Cyclo-static Multiprocessor Scheduling for the Optimal Realization of Shift-Invariant Flow Graphs," *Proc. 1985 Int. Conf. Acoustics, Speech and Signal Processing*, pp. 1834-1387, March 1985.

2. S. H. Lee, C. J. M. Hodges, and T. P. Barnwell III, "An SSIMD Compiler for the Implementation of Linear Shift-Invariant Flow Graphs," *Proc. 1985 Int. Conf. Acoustics, Speech and Signal Processing*, pp. 1664-1667, March 1985.

3. M.J.T. Smith and T.P. Barnwell, III, "A New Formalism for Describing Analysis/Reconstruction Systems based on Maximally Decimated Filter Banks," *Proc. 1985 Int. Conf. Acoustics, Speech and Signal Processing*, pp. 521-524, March 1985.

Papers Submitted:

1. Mark J. T. Smith and Thomas P. Barnwell, III, "A Unifying Filter Bank Theory for Frequency Domain Coding", (submitted) *IEEE Transactions on Acoustics, Speech and Signal Processing.*

2. S. H. Lee and T. P. Barnwell III, "A Topological Sorting and Loop Cleansing Algorithm for a Constrained MIMD Compiler of Shift-Invariant Flow Graphs", *Proc. 1986 Int. Conf. Acoustics, Speech and Signal Processing*, Tokyo, Japan, April, 1986.

3. D. A. Schwartz, T. P. Barnwell III, and C. J. M. Hodges, "The Optimal Synchronous Cyclo-Static Array: A Multiprocessor Supercomputer for Digital Signal Processing", *Proc. 1986 Int. Conf. Acoustics, Speech and Signal Processing*, Tokyo, Japan, April, 1986.

WORK UNIT NUMBER 3

TITLE: Two-Dimensional Optical Storage and Processing

SENIOR PRINCIPAL INVESTIGATOR: T. K. Gaylord, Regents' Professor

SCIENTIFIC PERSONNEL:

M. G. Moharam, Associate Professor
E. I. Verriest, Assistant Professor
M. M. Mirsalehi, Assistant Professor
E. N. Glytsis, Graduate Research Assistant (Ph.D. candidate)
A. Knoesen, Graduate Research Assistant (Ph.D. candidate)
R. S. Weis, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long-term scientific objective of this research is to develop broadly based, theoretical and experimental knowledge of high-capacity, high-troughput, two-dimensional optical information storage and two-dimensional optical signal processing. This would bring together a range of concepts from basic physics to signal processing in its most generalized form. An optical digital parallel processor based on truth-table look-up processing implemented in the form of a content-addressable memory would be developed and tested.

RESEARCH ACCOMPLISHMENTS:

A. Optical Data Processing Instrumentation

Routine passive techniques such as temperature and air current control are not adequate to provide interference fringe stabilization in holographic optical data processing experiments. A successful active phase stabilization system that can be adapted to a variety of experimental configurations was developed. It utilizes a synchronous lock-in amplifier and an electro-optic phase modulator to provide real-time stabilization of the interference fringe pattern. Both a video detection method and a direct optical detection were evaluated in conjunction with the phase stabilization system.

This work was published in *Applied Optics*.

B. Lithium Niobate Properties

In optical signal processing, lithium niobate is widely used due to its favorable electro-optic and photorefractive properties. This ferroelectric material also has important piezoelectric, elastic, and photoelastic properties. The important tensor physical properties and their mathematical descriptions were compiled. The essential features of its crystal structure were deduced and illustrated. Numerous errors in property values and crystal structure dimensions appearing in the literature were corrected.

The results of this work appeared in an invited review paper in *Applied Physics*.

C. Integrated Optical Anisotropic Waveguide Analysis

The surface impedance/admittance approach was shown to be very useful in describing the reflection and refraction of electromagnetic waves in an anisotropic medium incident upon a boundary with another anisotropic material. This valuable approach was reviewed and extended to the case of anisotropic dielectric slab waveguides used in integrated optical signal processing.

This work was published in *Applied Physics*.

D. Grating Diffraction

The rigorous coupled-wave analysis of grating diffraction developed under JSEP support by us is the first unified treatment that applies to both dielectric and metallic materials and to both planar (slab) and surface-relief (corrugated) structures. The exact formulation was presented along with the details of the solution in terms of state variables. Then using a series of assumptions, the rigorous theory is shown to reduce to the various existing approximate theories in the appropriate limits. The effects of these fundamental assumptions in the approximate theories were quantified.

This work was published in the *Proceedings of the IEEE*.

E. Optical Digital Parallel Processing

It was shown that digital parallel processing could be implemented using optical truth-table look-up techniques. With optical-logic-based pattern recognition, a content-addressable memory can be constructed. The use of the EXCLUSIVE OR and NAND logic operations to achieve content addressability were quantified. This memory system can be used to perform digital truth-table look-up processing and the requirements for 4-, 8-, 12-, and 16-bit addition and multiplication were given. The use of a binary-coded residue number system dramatically reduces the required storage capacity.

This work was published in *Optical Engineering*.

PUBLICATIONS:

Thesis:

1. M. M. Mirsalehi, "Two-Dimensional Optical Storage and Processing," Ph.D. Thesis, Georgia Institute of Technology, August, 1985.

Journal Articles:

1. C. C. Guest and T. K. Gaylord, "Phase stabilization system for real-time image subtraction and logical EXCLUSIVE OR processing," *Applied Optics*, vol. 24, pp. 2140-2144, July 15, 1985.

2. R. S. Weis and T. K. Gaylord, "Lithium niobate: Summary of physical properties and crystal structure," *Applied Physics A*, vol. 37, pp. 191-203, August 1985. (invited)

3. A. Knoesen, M. G. Moharam, and T. K. Gaylord, "Surface impedance/admittance approach for solving isotropic and anisotropic propagation problems," *Applied Physics B*, vol. 38, pp. 171-178, November 1985.

4. T. K. Gaylord and M. G. Moharam, "Analysis and applications of optical diffraction by gratings," *Proceedings of the IEEE*, vol. 73, pp. 894-937, May 1985. (invited)

5. T. K. Gaylord, M. M. Mirsalehi, and C. C. Guest, "Optical digital truth-table look-up processing," *Optical Engineering*, vol. 24, pp. 45-58, January/February 1985. (invited)

6. T. K. Gaylord and M. M. Mirsalehi, "Truth-table look-up processing: Number representation, multilevel coding, and logical minimization," *Optical Engineering*, vol. 25, pp. 22-28, January/February 1986. (invited)

Journal Papers Accepted:

1. M. M. Mirsalehi and T. K. Gaylord, "Comments on direct implementation of discrete and residue-based functions via optimal encoding: A programmable array logic approach," *IEEE Transactions on Computers*, vol. C35, pp. xxx-xxx, July 15, 1986.

2. M. M. Mirsalehi and T. K. Gaylord, "Multilevel coded residue-based content-addressable memroy optical computing," *Applied Optics*, vol. 24, pp. xxx-xxx, 1986.

3. M. M. Mirsalehi, T. K. Gaylord, and E. I. Verriest, "Integrated optical givens rotation device," *Applied Optics*, vol. 25, pp. xxx-xxx, May 15, 1986.

INTERACTIONS AND TECHNOLOGY TRANSFER:

The use of truth-table look-up content-addressable memory optical computing for adaptive antenna beamforming was discussed with the US Army MICOM Research Directorate in Huntsville, Alabama.

The analysis of interdigitated-electrode produced electric fields in integrated optical anisotropic waveguides was discussed with the US Army Research and Development Center in Dover, New Jersey.

WORK UNIT NUMBER 4

TITLE: Two-Dimensional Optical/Electronic Signal Processing

SENIOR PRINCIPAL INVESTIGATOR: W.T. Rhodes, Professor

SCIENTIFIC PERSONNEL:

R.W. Stroud, Graduate Research Assistant (Ph.D. candidate)
J.M. Hereford, Graduate Research Assistant (Ph.D. candidate)
J.T. Sheridan, Graduate Research Assistant (M.S. candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to gain a good understanding of the capabilities and limitations of hybrid optical/electronic methods for high throughput processing of 2-D signal information and to develop new and widely applicable techniques based on such methods. Emphasis is placed on establishing the capabilities of systems that mate well with digital signal processing systems.

RESEARCH ACCOMPLISHMENTS:

A. Bipolar Incoherent Spatial Filtering

Our original objective in this area was to develop effective methods for bipolar spatial filtering using incoherent optical systems that are simple to implement and efficient with respect to light utilization. That objective was augmented with the additional goal of maximizing overall system dynamic range in the case where optical and digital subsystems are combined with a scanning operation in between.

Research in this area was essentially completed during 1984 and the early part of 1985. During the term of this report the writing of a doctoral dissertation was completed and three papers prepared for publication.

B. Morphological Shape Transformations.

Investigations were begun this past fall on highspeed opto-electronic methods for implementing morphological shape transformations (e.g., erosions, dilations, openings, closings, and general rank-order processes) on binary images and nonlinear filtering operations (e.g., median filtering) on gray-scale images. Morphological transformations, which involve the interaction of a shape under study with a structuring element, are being used more and more in pattern recognition and classification for such things as quality control and robotic vision. Some of the basic operations are quickly performed using binary digital logic circuitry. Others, however (e.g., skeleton decomposition, where the pattern under study is reduced to primitive components), are sufficiently complex that TV-frame-rate processing is difficult to achieve. The schemes we are investigating perform the necessary operations in parallel. Real-time operation depends on finding a device that, like high contrast film, will perform a hard limiting operation on an image, but essentially instantaneously. Such devices are currently under development (e.g., at GTE laboratories), and the methods we are investigating appear to have good potential for success in a real-time environment.

Figure 1 illustrates how the operation is performed. A binary input pattern is presented to a shift-invariant imaging system and a blurring operation performed (Fig. 1a). In the figure the blur function, which plays the role of the structuring element in the transformation, is a disk, though other shapes are easily accommodated. The resultant blurred image is then hard limited. If the threshold is set for a high intensity, an erosion results (Fig. 1b); with a low intensity threshold, a dilation results (Fig. 1c). Setting the threshold at the 50% level results (with binary input and blur functions) in a median operation. Other threshold levels can be used to obtain other rank-order processing operations, assuming the input and blur functions are binary. These simple operations have been successfully demonstrated in the laboratory and will be presented at a conference in April 1986.

C. Time-Integration Optical Processing Research

Work that began under this program in connection with a Fourier transform scanning hybrid image processing system has evolved to center on the general problem area of bias buildup, signal-to-bias ratio, and signal-to-noise ratio in time-integration optical processing. This is a generic problem that affects several important classes of optical signal processing, including time-integration acousto-optic processing of radar and communication signals and incoherent holography.

In a mathematical study we have considered the implications of an image synthesis operation of the form

$$I(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(u,v)\cos^2[2\pi(ux+vy) + \theta(u,v)]dudv,$$

which can be written as

$$I(x,y) = \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(u,v)\{1 + \cos[2\pi(2ux+2vy) + 2\theta(u,v)]\}.$$

The first form suggests the name "raised cosine" synthesis. The elemental components of this synthesis, though similar to Fourier components, are biased, each component having the necessary and sufficient bias to assure nonnegativity. The relationship to a normal Fourier transform is emphasized by writing

$$I(x,y) = \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(u,v)dudv + \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(u,v)\cos[2\pi(2ux+2vy) + 2\theta(u,v)]dudv.$$

The second term, although in unconventional form, is essentially a real-valued Fourier synthesis integral and can represent any real-valued function f(x,y) satisfying the usual conditions. The first term is a bias that depends on the entire range of spatial frequencies in the image. Details of the relationship between A(u,v) and the 2-D Fourier transform of f(x,y) have been studied, both in continuous and sampled versions.

This particular synthesis is of considerable practical interest to us because it represents the minimum-bias image that can be recorded using time integration optical processing methods. Its properties and characteristics have been studied in connection with image synthesis, incoherent holography, and more general time-integration optical signal processing where an output distribution is built up of biased cosine fringe patterns.

Of particular use in numerical studies has been the relationship between a conventional Fourier series representation for an image,

$$I(x,y) = \{ \sum_{m,n} F_{m,n} \exp[j2\pi(mx+ny)] \} \mathrm{rect}(x,y),$$

and the corresponding raised cosine synthesis,

$$I_{rc}(x,y) = 2 \sum_{m,n} |F_{m,n}|(1 + \cos[2\pi(mx+ny) + \theta_{m,n}])\mathrm{rect}(x,y),$$

where $\theta_{m,n}$ is the phase of $F_{m,n}$ and the summation excludes the 0,0 component. This relationship allows us to simulate on the computer a number of important optical signal processing operations that would be difficult for us to set up in the laboratory.

In this general area we have also considered characteristics of the output plane detector that can improve overall processor signal-to-noise ratio. The problem generally is that in such processing bias uses up a large fraction of the detector dynamic range. Of special interest to us for certain applications is the optimum use of photographic film for the detector. We have showed how optimum performance can be obtained in the particular case of bleached silver halide holograms made with low-contrast exposures. The results of our work will be presented at a holography conference in April 1986, and a manuscript for publication is in preparation.

D. Opto-Electronic Processor Architectures

We have continued our study of linear algebraic optical processing, giving an invited review paper on the subject at a recent SPIE Critical Review of Technology in the area of Highly Parallel Signal Processing Architectures. Work in this area has been frustrated by largely negative conclusions about the ability of optical algebraic processors to compete with their all-electronic counterparts. Our studies have extended to architectural concepts exploiting ultrashort optical pulses and their interactions in appropriate nonlinear optical media. Some preliminary conclusions, dealing largely with the difficulties associated with such methods, have been presented at a recent SPIE conference on Optical Computing.

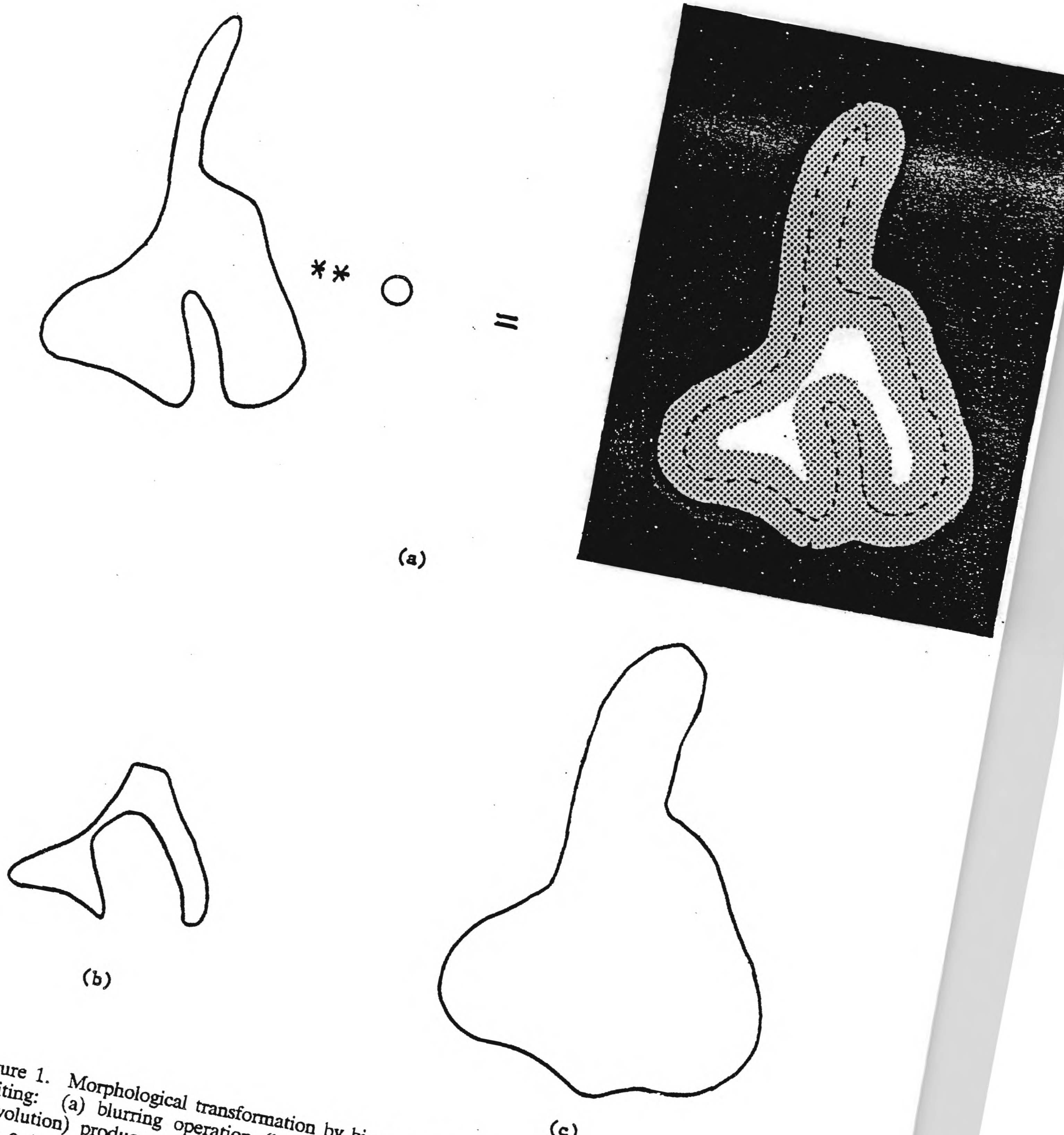

Figure 1. Morphological transformation by binary image blurring and hard limiting: (a) blurring operation (here with a disk; blurring represented by convolution) produces an image that is bright in the center, dark at edges, with a transition region in between; (b) erosion results from hard limiting at a high threshold; (c) dilation results from hard limiting at a low threshold.

PUBLICATIONS:

Dissertations:

1. Joseph N. Mait, "Pupil Function Optimization for Bipolar Incoherent Spatial Filtering," Ph.D. Thesis, Georgia Institute of Technology, June, 1985.

Journal Articles:

1. Joseph N. Mait, "Existence Conditions for Two-Pupil Synthesis of Bipolar Incoherent Pointspread Functions," (accepted) *Journal of the Optical Society of America A*, vol. 3, pp. xxx-xxx (1986).

Papers at Conferences without Proceedings:

1. W. T. Rhodes and R. W. Stroud, "Forming Parallel Fringes of Variable Spatial Frequency," presented at 1985 Annual Meeting of the Optical Society of America, Washington, D.C., October 1985.

2. E. S. Gaynor and W. T. Rhodes, "Exposure Optimization for Incoherent Computer Holography," presented at 1985 Annual Meeting of the Optical Society of America, Washington, D.C., October 1985.

Papers Submitted:

1. W. T. Rhodes and K. S. O'Neill, "Morphological Transformations by Hybrid Optical-Electronic Methods," in *Hybrid Image Processing*, D. Casasent and A. Tescher, eds. (Proc. SPIE, vol. 638, 1986).

2. W. T. Rhodes, "Optical Matrix-Vector Processors: Basic Concepts," in *Highly Parallel Signal Processing Architectures*, K. Bromley, ed. (Proc. SPIE, vol. 614, 1986).

3. W. T. Rhodes and J. A. Buck, "Optical Computing and Nonlinear Optics," in *Optical Computing*, J. Neff, ed. (Proc. SPIE, vol. 625, 1986).

4. J. N. Mait and W. T. Rhodes, "Two-Pupil Synthesis of Optical Transfer Functions: Pupil Function Relationships," submitted to *Optics Letters*.

5. J. N. Mait, "Pupil Function Design for Bipolar Incoherent Spatial Filtering," submitted to *Journal of the Optical Society of America A*.

6. W. T. Rhodes, "The Optical Margin," to be published in *Optics News*.

INTERACTIONS WITH DOD LABS:

Met with Dr. Jacques Ludmann, RADC, Hanscom Field, June 1985.

Met with Captain Greg Swietek, HQ FASC/DLAC, Andrews AFB, November 1986, for discussions on optical computing.

Met with P. Denzil Stilwell, Radar Division, Naval Research Laboratory, November 1986, for discussions on optical processing for fiber-optic-feed phased array radar system.

WORK UNIT NUMBER 5

TITLE: Optimal Multiprocessor Structures for the Implementation of Digital Signal Processing Algorithms on High Density Integrated Circuits

SENIOR PRINCIPAL INVESTIGATOR: J. H. Schlag and D. A. Schwartz

SCIENTIFIC PERSONNEL:

H. Forren, (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

To develop techniques for the automatic generation of optimal or highly efficient implementations of digital signal processing algorithms for synchronous multiprocessor VLSI architectures.

RESEARCH ACCOMPLISHMENTS:

In April of 1985 this work unit was split off from Work Unit 2 (Multiprocessor Architectures for Digital Signal Processing). Due to the initial overlap in personnel (D. A. Schwartz) there has been an overlap in research areas. While both units are interested in the problem of generating highly efficient implementations for a large class of DSP algorithms using multiple synchronous processors, this unit specifically focuses on the issues related to VLSI implementation constraints. The emphasis is on complexity tradeoffs and interprocessor communications. The multiprocessor systems are being analyzed in the context of cyclo-static solutions to DSP algorithms. This is due to the powerful ability to draw broad formal conclusions of the optimality of the resulting system with respect to several optimality criteria of interest (i.e. processor utilization optimal, delay optimal, rate optimal and communications optimal), in the case of cyclo-static solutions.

In the research area of cyclo-static solutions, the ability to find solutions has been expanded from the class of recursive filter-like algorithms to general iterative non-recursive algorithms. It has also been noted that the numerical solution of ordinary differential equations is a special case of the recursive filter-like class.

Simple sufficient conditions for a recursive algorithm to have a hardware realization that is rate optimal, processor optimal and delay optimal have been established. Simple sufficient conditions have also been found for the fully-static class of cyclo-static solutions to exist. This has come from the Ph.D research of H. Forren.

Previous work on cyclo-static solutions has focused on a more general purpose homogeneous multiprocessor. Statements about processor (utilization) optimality have been with respect to processor, as an atomic unit, utilization. When examined in the area of algorithmically specialized processor to be realized in VLSI, for a specific task, it becomes apparent that though processors may be ideally utilized, internally the processor may be only partially utilized. For example, in the filtering problems previously examined, it was assumed that the homogeneous processor could perform a (floating point) multiply or a (floating point) addition. While a processor may be doing one of theses operations at all times, resulting in a processor optimal solution, internally the processor may be only partially utilized is the different functions (addition and multiplication) use disjoint resources. Cyclo-static solutions have therefore been expanded to non-homogeneous processors, i.e. adders and multipliers. This was accomplished by associating a separate principal lattice vector with each type of processor.

A new cyclo-static compiler is under development that will incorporate the capacity for inhomogeneous processor solutions as well as applying some new ideas on methods for increasing the efficiency of the compiler in order to handle more complex problems.

The basic ideas of cyclo-static systems from this work unit and from work unit 2 has led to a technology transfer to develop a small scale supercomputer signal processor under contract from the Defense Agencies Research Projects Administration (DARPA). The small scale model is called OSCAR (Optimal Synchronous Cyclo-static ARray), and will be a four by four square array of special floating point processor with and expected throughput of approximately 80 MFLOPS. OSCAR will provide a test bed architecture for real time algorithm development in areas such as image processing, moving image processing etc. as well as a test bed for the development of compilers and other tools for the automatic determination of highly parallel realizations of digital signal processing algorithms. In additions OSCAR has been designed to support several models of architectures for which there are currently no formal tools for finding parallel realizations to, but which appear to be promising research areas.

OSCAR promises to be an important test vehicle for validating the current classes of cyclo-static solutions and to provide a direct mechanism for comparison to other approaches to multiprocessing such as systolic and wavefront array processing. The architectual design of OSCAR's communications has clarified many aspects that had been previously overlooked and has led to a clearer understanding of some of the theoretical tradeoffs in communications complexity. The design of OSCAR has amplified the importance of the tradeoff between the communications complexity, for a given performance goal, and the ability to design a processor that can be effectively programed.

Research is still in the start-up phase of examining a complexity theory approach to determining a minimum communications support for a given algorithm. Given a communications support (that is minimal or is fixed in a target machine), work is continuing on efforts to find more efficient algorithms to map applications algorithms onto the communications support. Binary tree communications support are know to embed efficiently in a planar constraint (VLSI chip), however they do not correspond well to current cyclo-static solutions. Work is continuing to find extensions of cyclo-static solutions that have better planar communications embedding. Initial results from a method that maps communications distance into communications delay appear promising.

WORK UNIT NUMBER 6

TITLE: Electromagnetic Measurements in the Time and Frequency Domains

SENIOR PRINCIPAL INVESTIGATOR: G. S. Smith, Professor

SCIENTIFIC PERSONNEL:

J. D. Nordgard, Professor
W. R. Scott, Jr., Graduate Research Assistant (Ph.D. candidate)
C. E. Davis, Graduate Research Assistant (M.S. Candidate)

SCIENTIFIC OBJECTIVE:

The broad objective of this research is to develop new methodology for making electromagnetic measurements directly in the time domain or over a wide bandwidth in the frequency domain. This research includes the development of the theoretical analyses necessary to support the measurement technqiues. One aspect of the research is the systematic study of radiating structures placed near or embedded in material bodies. In a practical situation the radiator might serve as a diagnostic tool for determining the geometry, composition or electrical constitutive parameters of the body.

RESEARCH ACCOMPLISHMENTS:

The research conducted during the last year was concentrated on the topic "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas." This research involved the study of three separate configurations for measuring the constitutive parameters of a material:

A. the open-circuited coaxial line of general electrical length;

B. the monopole antenna of moderate electrical size;

C. the monopole antenna of general electrical length.

The research involving all three configurations is now complete, and journal articles describing the results have been published or submitted for publication.

A brief description of the research accomplishments for these topics follows.

A. Open-Circuited Coaxial Line

The open-circuited coaxial line of general length was studied as a sample holder for broadband measurements of the dielectric permittivity. The multivalued nature of the inverse function was described in detail. The error that results from passing onto the wrong branch was developed. The error in the measured permittivity due to the inaccuracies in the instrumentation was also analyzed. Contour graphs were constructed that quantify the effects of these two errors on the measured permittivity. The measurement technique was tested by measuring several alcohols with know permittivity. The study of the open-circuited coaxial line provided valuable experience that was applied to the measurement of the electrical constitutive parameters of materials using monopole antennas.

B. and C. Monopole Antennas

Two general procedures were developed for measuring the electrical constitutive parameters of materials using monopole antennas.

In the first procedure, a normalized impedance that is only a function of the dimensionless parameter kh (wave number • length) is defined for the antenna. The normalized impedance is expressed as a rational function, and the coefficients in this function are determined from a measurement of the impedance in a standard medium. The impedance measured in a material with unknown constitutive parameters is used with the rational function to form a polynomial in kh. The constitutive parameters of the medium are determined from a root of this polynomial. The measurement technique was implemented for a rational function of order three. The constitutive parameters of the alcohol 1-butanol and saline solutions were measured over a range of frequencies using the technique with cylindrical and conical monopole antennas. The measured constitutive parameters are in good agreement with those determined by previous investigators.

The second procedure, like the first, makes use of the normalized impedance of the antenna and a calibration of the antenna in a standard material with known constitutive parameters. However, in this procedure a numerical inverse is constructed from the calibration data and used to obtain the unknown permittivity of a material from the measured input impedance of the antenna. This procedure can be used with any size monopole antenna. The measurement technique was used to measure the constitutive parameters of the alcohol 1-butanol and saline solutions over broad frequency ranges (f to 200 f) with a single antenna. The antenna was as long as three wavelengths in the medium at the highest frequencies. The measured parameters for these materials were not good agreement with the expected values.

PUBLICATIONS:

Theses:

1. W. R. Scott, Jr., "Dielectric Spectroscopy Using Shielded Open-Circuit Coaxial Lines and Monopole Antennas of General Length," *Ph.D. Thesis, School of Electrical Engineering, Georgia Institute of Technology*, Atlanta, Georgia, October 1985.

Journal Articles (published or accepted):

1. G. S. Smith and J. D. Nordgard, "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas," *IEEE Trans. Antennas and Propagat.*, Vol. AP-33, pp. 783-792, July 1985.

2. W. R. Scott, Jr., and G. S. Smith, "Error Analysis for Dielectric Spectroscopy Using Shielded Open-Circuited Coaxial Lines of General Length," accepted *IEEE Trans. Instrumentation and Meas.*.

Papers at Conferences with Proceedings:

1. G. S. Smith, "Measurement of the Permittivity of Materials Using Monopole Antennas," *1985-IEEE Antennas and Propagation Society, International Symposium*, Vancouver, Canada, pp. 517-520, June 1985.

2. W. R. Scott, Jr. and G. S. Smith, "Dielectric Spectroscopy Using Open-Circuited Coaxial Lines of General Length," *1985 North American Radio Science Meeting*, Vancouver, Canada, pg. 37, June 1985.

Papers Submitted for Publication:

1. W. R. Scott, Jr. and G. S. Smith, "Error Corrections for an Automated Time-Domain Network Analyzer," submitted for publication.

2. W. R. Scott, Jr. and G. S. Smith, "Dielectric Spectroscopy Using Monopole Antennas of General Electric Length," submitted for publication.

INTERACTION WITH DOD LABS

During the year, a study entitled "Hardened Antenna Technology Assessment" was begun for the Air Force (RADC, Griffis, AFB). This study makes use of analyses of buried antennas performed on the Joint Services Electronics Program.

WORK UNIT NUMBER 7

TITLE: Automated Radiation Measurements for Near- and Far-Field Transformations

SENIOR PRINCIPAL INVESTIGATOR: E.B. Joy, Professor

SCIENTIFIC PERSONNEL:

W.M. Leach, Jr., Professor
J.M. Rowland, Graduate Research Assistant (Ph.D. candidate)
R.E. Wilson, Graduate Research Assistant (Ph.D. candidate)
A.J. Julian, Jr., Graduate Research Assistant (Ph.D. candidate)
Y. Kanai, Graduate Research Assistant (M.S. candidate)

SCIENTIFIC OBJECTIVE:

The long term objective of this research is to understand the near field and far field coupling between antennas in the presence of scatterers. Special emphasis is placed on determination of limits of accuracy in the measurement of the fields radiated or scattered by an antenna-under-test by a second antenna and to develop techniques and computer algorithms for compensation of such measurements due to known geometrical or electromagnetic anomalies.

RESEARCH ACCOMPLISHMENTS:

A. Near-Field Radar Cross-Section Measurement Technique

Initial work has been completed on the plane wave scattering description of near-field coupling among three antennas. Antenna number one is viewed as the source of electromagnetic radiation, antenna number two is viewed as a scatterer of electromagnetic energy and the third is viewed as the receiver of electromagnetic radiation. This general formulation can model both bistatic and monostatic radar cross section measurement systems, both in the near-field and far-field. The model is capable of predicting both far-field bistatic and monostatic radar cross-sections from near-field measurements. The model has been verified for a single plane wave illumination, bistatic measurement. A monostatic near-field radar cross-section measurement was performed using a planar surface near-field measurement system with good results. These measurements were made on a simple (a flat plate) target. Measurements of other targets which will more fully test the technique are planned. These results were presented at the 1985 Meeting of the Antenna Measurement Techniques Association.

B. Sampling Requirements for Spherical Surface Near-Field Measurements

A sample spacing requirement was developed in the spherical surface near-field measurement technique. The rate of decay of evanscent energy storage near an antenna was investigated and found to be bounded by a Hankel function of the second kind of order N. The order N also specifies the theta and phi orders and thus sampling in theta and phi. Results were presented at the 1985 Meeting of the Antenna Measurement Techniques Association. These results showed that the sampling depended on the electrical size of the antenna under test and the distance from the antenna under test to the measurement sphere. Results were also presented which showed that the sampling requirement for spherical surface measurement approaches the well known sampling requirement for the planar surface as the radius of the spherical surface becomes large.

This result is important in the correct measurement of near-field or far-field patterns of antennas. Under-sampling causes aliasing and measurement error. Previous sampling requirements resulted in inaccuracies. Large amounts of redundant data were often collected and processed to overcome the lack of a sampling criterion.

This sampling criterion will be used in the measurement, testing, aligning and accepting of ground/ship based, air based and space based radar and communications antennas.

PUBLICATIONS:

Short Course Texts:

1. J. Frank and E.B. Joy, *Phased Array Antenna Technology*, Technology Service Corporation, 1984.

2. E. B. Joy, A.L. Maffett and J. Frank, *Radar Cross-Section Measurement Techniques*, Technology Service Corporation, 1984.

Editor of Meeting Proceedings:

1. E. B. Joy (Editor), Proceedings of the 1985 Meeting of the Antenna Measurement Techniques Association Meeting, Melbourne, FL, October 29-31, 1985, p. 421.

Papers in Conference Proceedings:

1. E. B. Joy and J. B. Rowland, Jr., "Sample Spacing and Position Accuracy Requirements for Spherical Surface Near-Field Measurements," *Proceedings of the 1985 IEEE/AP-S International Symposium*, Vancouver, B.C., June 17-21, 1985, pp. 682-692.

2. E. B. Joy, Near-Field Radar Crossection Measurement," *Proceedings of the Antenna Measurement Techniques Association Workshop on RCS Measurement Techniques*, Vancouver, B.C., June 21, 1985.

3. E. B. Joy and J. B. Rowland, Jr., "Sample Spacing Requirements for Spherical Surface Near-Field Measurements," *Proceedings of the 1985 Antenna Measurement Techniques Association Meeting*, Melbourne, FL, October 29-31, 1985, pp. 2-1, 2-10.

4. K. W. Cozad and E. B. Joy, "An Outdoor VHF Cylindrical Surface Near-Field Range," *Proceedings of the 1985 Antenna Measurement Techniques Association Meetings*, Melbourne, FL, October 29-31, 1985, pp. 4-1, 4-8.

5. E. B. Joy, O. D. Asbell and R. C. Johnson, "Feasibility of a Large Outdoor Compact Range," *Proceedings of the 1985 Antenna Measurement Techniques Association Meeting*, Melbourne, FL, October 29-31, 1985, pp. 11-1, 11-6.

6. E. B. Joy, B. K. Rainer and B. L. Shirley, "Monostatic Near-Field Radar Cross-Section Measurement," *Proceedings of the 1985 Antenna Measurement Techniques Association Meeting*, Melbourne, FL, October 29-31, 1985, pp. 24-1, 24-11.

Papers Submitted:

1. W.M. Leach, Jr., "A Plane-wave Spectrum Development of the Spherical Surface Near-Field Coupling Equation," (submitted) *IEEE Transactions on Antennas and Propagation*.

TECHNOLOGY TRANSFER

1. U.S. Navy: M.I.T. Lincoln Laboratory is developing a high performance surveillance radar system which incorporates a shipboard mounted ultra-low sidelobe planar phased array antenna. The array has a 5-meter by 10-meter aperture and -55 dB rms sidelobe levels. M.I.T. Lincoln Laboratory will install a multi-million dollar plane-polar near-field measurement system to test and align the phased array. To achieve the desired measurement and alignment accuracies, the K-correction probe position error compensation technique and algorithm developed under JSEP sponsorship will be transferred to M.I.T. Lincoln Laboratory. (The request for proposal on the facility specifies use of this technique).

2. Harris Corporation: A cylindrical surface near-field measurement system was designed and constructed at Harris Corporation, Quincy, IL, using the error analysis simulation developed under JSEP sponsorship for the specification of the required electrical and mechanical apparatus.

ANNUAL REPORT
Joint Services Electronics Program
DAAG29 - 84 - K - 0024
January 1, 1986 - December 31, 1986

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

JANUARY 1987

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

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This is an annual report on research conducted under the auspices of the Joint Services Electronics Program. Specific topics covered are: digital signal processing, parallel processing architectures, two-dimensional optical storage and processing, hybrid optical/digital signal processing, electromagnetic measurements in the time domain, and automatic radiation measurements for near-field and far-field transformations.

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TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

January, 1987

School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

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TABLE OF CONTENTS

I. OVERVIEW

This annual report covers the second year of research carried out under Contract DAAG29-84-K-0024. The research is part of the Joint Services Electronics Program and is administered by the U. S. Army Research Office. Research activities are concentrated in two areas: (1) Two-Dimensional Signal Processing and Storage, and (2) Theory and Application of Electromagnetic Measurements.

The research in two-dimensional signal processing and storage is concentrated in five major areas. These areas overlap and the research activities interact and reinforce one another. Research in Work Unit Number 1, *Multidimensional Digital Signal Processing*, is concerned with the theory, design, and implementation of digital signal representations and digital signal processing algorithms and systems. Work Unit Number 2, *Multiprocessor Architectures for Digital Signal Processing*, focusses upon hardware and software problems in the use of multiport memories and multiple processors for high-speed implementations of digital signal processing algorithms. The research in Work Unit Number 3, *Two-Dimensional Optical Storage and Processing*, is concerned with problems of using holographic information storage as the basis for multiport memories and for optical computation. Work Unit Number 4, *Two-Dimensional Optical/Electronic Signal Processing*, is concerned with the theory, implementation, and application of combined optical and electronic digital signal processing techniques. Work Unit Number 5 is directed toward problems in the design of VLSI implementations of digital signal processing systems.

The other two work units in the JSEP program are concerned with electromagnetic measurements. In Work Unit Number 6, *Electromagnetic Measurements in the Time- and Frequency-Domains*, research is concerned with both theoretical and experimental investigations of the use of time-domain and frequency-domain methods for measuring the characteristics of materials and electromagnetic systems. Work Unit Number 7, *Automated Measurements for Near- and Far-Field Transformations*, is concerned with assessing the accuracy of computed fields on the surface of lossy radomes and with compensating for probe effects when near-field measurements are made on spherical and arbitrary surfaces.

The report begins with the Lab Director's summary of the accomplishments during the period January 1, 1986 to December 31, 1986. Following this are brief reports on the individual work units. These reports list personnel supported and discuss in general terms the research that was carried out during the reporting period. Also included in each work unit report is a complete list of publications on the research during this period. Complete copies of these publications are available in the Annual Report Appendix.

II. SIGNIFICANT RESEARCH ACCOMPLISHMENTS

The following accomplishments are, in the judgement of the laboratory directors, of particular significance and potential and are therefore worthy of special mention.

2.1 Experimental Demonstration of Parallel Logic Operations

A major achievement of the continuing research in Work Unit Number 3 was the experimental demonstration of both parallel EXCLUSIVE OR and parallel NAND logic operations to achieve content addressability and thus digital parallel truth-table look-up processing. This work was published in the invited paper in *Optical Engineering*.

This result provides practical experimental demonstrations of optical digital parallel processing using array logic. It is highly significant since it demonstrates that large scale parallel digital processors can be implemented optically. Potential applications include remote sensing, air traffic control, synthetic aperture radar imaging, missile guidance, and adaptive antenna array beamforming.

2.2 A Unified Theory of Translation-Invariant Image Processing Systems

A major achievement of the research in Work Unit Number 1 is the development of a new theory for representing images and image processing systems. Maragos, in his Ph.D. thesis, has developed a new theory of translation-invariant systems in which both signals and systems are fundamentally represented by sets rather than by functions. This leads to a theory of signals and systems in which geometric structure is prominent. The theory has already been applied to gain new insight into the properties and implementation of many common image transformations and it potentially can serve as the basis for the design and implementation of new image transformations specifically directed toward enhancing, detecting, and coding of geometric structure in images.

2.3 Monostatic Near-Field Radar Cross-section Measurement

A monostatic near-field radar cross-section measurement of a simple target (a square flat plate) was performed on a planar surface near-field measurement system. The far-field monostatic radar cross-section was correctly determined from the near-field measurements. This demonstration was an important step in the process of developing the monostatic near-field radar cross-section technique. Should this technique become fully developed, the monostatic scattering of large (full scale) targets could be accurately measured. The near-field, intermediate field and far-field scattering properties are determined in one measurement set. Radar ananoloies such as glint can be accurately predicted from these measurements.

WORK UNIT 1

TITLE:

Multidimensional Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR:

R. W. Schafer, Regents' Professor

SCIENTIFIC PERSONNEL:

R. M. Mersereau, Professor
M. H. Hayes, Associate Professor
C. Au Yeung, Graduate Research Assistant (Ph.D. Candidate)
J. E. Bevington, Graduate Research Assistant (Ph.D. Candidate)
D. Y. Suh, Graduate Research Assistant (Ph.D. Candidate)
L. Hertz, Graduate Research Assistant (Ph.D. Candidate)
C. H. Richardson, Graduate Research Assistant (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to understand the means by which multidimensional signals such as images should be modelled and represented to facilitate the encoding, enhancement and automatic extraction of information from such signals, and to develop, analyze and extend computer algorithms for these purposes.

RESEARCH ACCOMPLISHMENTS:

A. Image Segmentation by Texture (Bevington, Mersereau)

This work has evolved from its initial exploration of the use of linear prediction coefficients as features for texture characterization to the development of a program for general purpose image segmentation. A split/merge algorithm has been developed which makes use of the maximum likelihood edge detector developed earlier along with simpler boundary detectors. This work has led to a statistical characterization of a number of edge detectors and an analysis of their performance on a variety of different edge types - points, grey level discontinuities, texture boundaries, cracks, ridges, and valleys. This study is continuing. The image segmentation program is being applied to the problem of low bit-rate image coding.

B. Constrained Signal Estimation

This project represents a continuation of a long standing project on iterative procedures for deconvolution of blurred images. This particular phase of the research is concerned with the development of techniques for iterative deconvolution using a maximum entropy criterion. Theoretical extensions from the power spectrum estimation problem have been developed which allow the results of that problem to be applied to deblurring. Four procedures for finding the maximum entropy solution have been developed and have been applied to the removal of lowpass blurs and also to the problem of reconstructing a multidimensional signal from its projections. Conditions on the existence of a feasible solution have been proven and the theory is currently being advanced to make the procedure more robust in the presence of measurement errors. Current efforts are also being directed toward the issue of reducing the complexity of the resulting algorithms.

C. Low Bit-Rate Encoding of Binary Video Signals

Research has begun on a project to efficiently encode two-level (binary) image sequences. Currently this work has not gone beyond the stage of recreating previously available results but it is expected that this project will make extensive use of ideas from mathematical morphology which were developed earlier.

D. Quadratically Convergent Deconvolution Algorithms

Iterative algorithms based on the method of successive approximations have become very popular for signal deconvolution due to the flexibility that they allow for the incorporation of signal constraints into the restoration. One of the limitations of these iterative algorithms is that they only achieve a linear rate of convergence. With a slight modification, however, it was shown that it is possible to achieve a quadratically convergent deconvolution algorithm. In effect, this modification corresponds to a reinitialization of the deconvolution algorithm with a new observation equation at each iteration. It was shown that the corresponding distortion operator h_k converges quadratically to an impulse and, as a result, the restoration x_k converges quadratically to x. Therefore, when the standard iteration requires k iterations to achieve a given reduction in the mean square error, the modified iteration will require only $\log_2(k)$ iterations.

E. Signal Modeling and Power Spectrum Estimation

Power spectrum estimation is a special form of signal reconstruction problem where one wants to determine the autocorrelation function or its Fourier transform from a finite time observation of a time series or from a noisy and truncated autocorrelation sequence. We have considered two problems related to signal modeling and the application of these models to spectrum estimation. The first problem is concerned with the modeling of a signal as the sum of sinusoids in white noise where the sinusoidal frequencies are varying as a function of time. Typically, with such a model an adaptive version of the Pisarenko harmonic decomposition would be applied to the data to extract the model parameters. By exploiting some properties of the Levinson/Durbin recursion, however, a new algorithm was developed for estimating the model parameters. In particular, an iterative procedure for finding the white noise power was proposed which uses a bisection search algorithm which terminates when the set of reflection coefficients corresponding a set of correlation values satisfy a specific set of conditions. Once the white noise power has been determined, the sinusoid frequencies are extracted by rooting the polynomial associated with the reflection coefficients. For nonstationary data, this algorithm was made into an adaptive algorithm where both the white noise power and the minimum eigenvector (eigenfilter) are recursively updated in time.

The second modeling problem considered was concerned with developing an autoregressive moving average lattice filter model for a linear time-varying system. As a result of this work a new ARMA lattice filter structure was developed which is consistent with the characteristics of the well-known autoregressive and moving average lattice filters. In particular, this ARMA lattice is realized in tems of a fully orthogonal lattice set of basis vectors and it evaluates all optimal lattice ARMA filters of lower order. In addition the ARMA lattice structure, a fast recursive least squares algorithm for the evaluation of the lattice filter coefficients was developed [18].

F. Theory and Application of Mathematical Morphology

A major accomplishment of our research during the present contract is the development of a general theory of translation-invariant systems. This general theory significantly extends the theory of mathematical morphology and it unifies a wide range of commonly used image processing operations under a common framework. Specifically we showed that any translation-invariant, increasing, system can be represented as a set union of erosions by all structuring elements belonging to a characteristic set of elements called the *kernel* of the system. Although the kernel of a system may generally contain an infinite number of elements, Maragos showed that a *basis* or smaller sufficient set of elements exists for a broad and interesting class of translation-invariant, increasing, systems. It was also shown that this *theory of minimal elements* applies to morphological filters, median filters, order-statistics filters, edge detectors, shape recognition transformations and an interesting class of linear shift-invariant systems. The theory has already lead to new insights into the properties of such systems and also to new approaches to the implementation of such systems.

The general theory has potential to be applied in the design and synthesis of image transformations. Since any translation-invariant increasing system can be represented as a union of erosions by its kernel elements, new systems can be defined by specifying the elements of the kernel basis. It is not known how to choose the kernel basis so as to create a system with prescribed desired properties. In order to learn how to do this we have begun to study some of the systems that we already know have a finite kernel basis, such as morphological opening and closing, median filters, order-statistics filters, and certain shape recognition transformations.

With this knowledge as a base, it may be possible to determine techniques for designing nonlinear image processing systems to perform specific processing functions such as noise removel, edge detection, and shape detection.

So far, our most impressive results have been for two-level (binary) images. However, most images are multi-level (greytone) images. Graytone images can be represented by a collection of sets which specify image pixels that exceed different thresholds. Indeed, if enough threshold sets are used, the graytone image can be represented with high accuracy. In many cases, it is desirable to obtain thresholded versions of an image with only a few different thresholds. An example is in representing images of integrated circuits or printed circuit boards where the image consists of regularly shaped geometric structures of only a few different types of material. Obtaining thresholded images that retain information on the basic geometric structures is a nontrivial task due to uneven lighting and focussing problems.

A new approach to multi-level thresholding has been developed. In this method, the threshold is adapted so as to insure that edges in the thresholded image are aligned with the edges of the original graytone image. In addition, thresholds are adapted spatially to account for non-uniform lighting, shadows, etc.

Research is now being directed at combining of contextual and other symbolic knowledge with the morphological transformations to obtain automatic algorithms for a variety of image analysis problems.

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Books or Chapters in Books

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2. Morris, C. E., Richards, M. A., and Hayes, M. H., "A generalized fast iterative algorithm for signal reconstruction", *submitted to 1987 Int. Conf. on Acoust., Speech, Sig. Proc.*

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4. Karlsson, E., and Hayes, M. H., "Performance analysis of new least squares ARMA lattice modeling algorithms", *submitted to 1987 Int. Conf. on Acoust., Speech, Sig. Proc.*

5. Maragos, P. A., and Schafer, R. W., "Morphological filters: Part 1--their set-theoretic analysis and relations to linear shift-invariant filters," *submitted to IEEE Trans. Acoustics, Speech, and Signal Processing.*

6. Maragos, P. A., and Schafer, R. W., "Morphological filters: Part 2--their relations with median and order-statistics filters," *submitted to IEEE Trans. Acoustics, Speech, and Signal Processing.*

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WORK UNIT NUMBER 2

TITLE:

Multiprocessor Architectures for Digital Signal Processing

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SCIENTIFIC OBJECTIVES

The primary objective of this proposed work unit is to develop systematic techniques for the automatic generation of provably optimal multiprocessor implementations for a broad class digital signal processing (DSP) algorithms and for a broad class of multiprocessors systems. Stated in another fashion, the goal of this research is to develop DSP "compilers," where the input is an algorithm specification and the output is a complete, optimal multiprocessor implementation.

A basic philosophy of this research has always been to perform the theoretical developments in the context of an actual multiprocessor system. The first system used for this purpose, an eight processor LSI-11/2 system [7-8], is now obsolete. For the future, the proposed research will be tested using a personal computer (PC) based multiprocessor utilizing AT&T DSP-32 processors.

BACKGROUND:

Over the past decade, the rapid development of digital integrated circuit techniques has caused increased interest in the area of parallel architectures for digital signal processing. Nowhere is this more evident than in multidimensional DSP algorithms, where the computational dimensions of the algorithms make serial processing unreasonable for virtually all real-time applications.

In any DSP oriented implementation, there will inevitably be a mix of both intrinsically serial and intrinsically parallel tasks which must be realized. Digital signal processing algorithms, as a group, are unique in that they are typically both highly computationally intense and also have a high degree of internal structure. For the purposes of this research, a DSP implementation is considered to be a realization which is dominated by its signal processing functions, and in which its non-signal-processing tasks (control, user interface, decision making, etc.) play a relatively minor role.

A. Algorithm Descriptions

For most of the past research from this work unit, the DSP algorithms have been specified as *shift-invariant flow graphs* (SIFG) [10]. A SIFG is defined as a directed graph in which all operations are specified at the nodes, and in which the branches are directed paths which specify the flow of data between nodes. The shift-invariant constraint requires that shifting the (set of) input sequences results only in a corresponding shift in the (set of) output sequences.

SIFG's are capable of representing a very large class of interesting DSP algorithms. Of course, they can easily represent all those systems which are representable by signal flow graphs. Hence, they can represent a large class of linear and non-linear as well as time-varying systems. In particular, they are capable of representing digital filters, DFT structures, FFT structures (indeed all fast discrete transform algorithms), correlation, convolution, homomorphic analysis, matched filtering, linear predictive analysis, LMS adaptive filter structures, direct form recursive least squares, and lattice form least squares, to name just a few. In addition, SIFG can also represent many algorithms which are not typically DSP algorithms, including a very large class of matrix operations as well as algorithms specified in terms of low level logic operations (e.g. a digital multiplier structure). In brief, SIFG's can represent all algorithms which do not include any data dependent branch operations. Clearly, the vast majority of DSP algorithms, as well as other equivalent algorithms, belong to this class.

A *fully specified flow graph* (FSFG) is a SIFG in which the nodal operations are additionally constrained to be the atomic (kernel) operations of the underlying constituent processors which are to be used in the realization. Thus the atomic operations represent the smallest granularity at which possible parallelism may be exploited [10]. The name *generic flow graph* is used to distinguish between those SIFG's that are also FSFG's and those SIFG's whose nodes are not all atomic operations.

B. Fully Specified Flow Graph Bounds

The distinguishing characteristic of the previous research is the underlying use of bounds on the optimal performance of an algorithm in the generation of the multiprocessor implementations. These bounds are characteristics of the graph defining the algorithm, not of the mechanism or type of realization. In all, three different bounds are used: the *iteration period bound* (previously called the *sample period bound* [10-12]), which is the minimum possible time between iterations of the algorithm; the *delay bound*, which is the minimum time between the availability of an input (set) and the availability of the corresponding output (set); and the *processor bound*, which is the minimum number of processors required to achieve the specified iteration period. Implementations which achieve the iteration period bound are said to be *rate-optimal*. Implementations which achieve the delay bound are called *delay-optimal*. Implementations which use the minimum possible number of processors for a specified iteration period are said to be *processor-optimal*.

The concept of bounds on the multiprocessor realization of flow graphs was first introduced in the context of signal flow graphs by Fettweis [13] and later extended by Renfors and Neuvo [14] and Schwartz and Barnwell [10-12]. The basic assumptions are that the algorithm to be implemented is represented as a FSFG, and that the algorithm is to be implemented on a synchronous multiprocessor. It is also assumed that the computation times for all the nodal operations are known. This condition is easily met in a homogeneous multiprocessor in which all the processing elements are the same. Nothing is assumed about the communications structure, I/O constraints, or the details of the realization. Hence, the resulting bounds reflect the absolute limits on computation rate and delay based on the atomic structure of the constituent processors.

Of course, many things besides the structure of the algorithm and the fundamental operational capability of the processors may limit DSP implementations. Clearly, things such as I/O bandwidths, external resource availability, the number of available processors, and the communications architecture may impact the achievable rate, delay, and processor efficiency of an algorithm. But in their own way, each of these aspects can be addressed and corrected. For a particular multiprocessor system and a particular FSFG, the above bounds are fundamental. Hence, if total implementations can be developed which achieve these bounds, then it is clear that no other implementations exist which can operate at a higher rate, with less delay, or with higher efficiency.

C. Systolic Processors

The area of systolic processors is currently attracting the attention of many researchers in parallel processing for scientific and signal processing tasks. The term systolic is assumed to mean a regular iterated array of computational elements with strict nearest neighbor communications. There is a global clock, and on every clock cycle each processor inputs data, operates on the data and outputs data at the end of the cycle. No information can flow further than one processor in one system clock cycle. Systolic processors are a special case of a static pipeline. Until recently the area was dominated by systolic solutions to specific problems, presented without verification or derivation. However, a number of systematic and rigorous approaches to systolic implementations have now appeared, including one from this research program [10-11].

Systolic processors are attractive because they appear to be well matched to many of the constraints implied by VLSI implementations, and more importantly because solutions are relatively easy to find. The problem is that systolic implementations are often over-constrained (global clock tick, static pipeline configuration, etc.), resulting in solutions which have low processor utilization and which cannot be rate-optimal or delay-optimal. Much of the research already performed as part of this work unit can be viewed as searching for implementations which overcome the fundamental limitations of systolic processors.

D. SSIMD Implementations

Historically, *Skewed Single Instruction Multiple Data* (SSIMD) implementations were the first class of solutions which could overcome the systolic constraints and consistently achieve rate-optimal, processor-optimal implementations with nearest neighbor communications for a large class of interesting algorithms [1,15-19]. In SSIMD, exactly the same program is executed on each of the processors in the multiprocessor, and that program realizes exactly one iteration of the flow graph. In an SSIMD program, all of the arithmetic operations appear as explicit instructions, but the delay nodes are transformed into input-output pairs. In this way, the delay structure in the flow graph becomes the communications structure in the SSIMD realization [1,15-19].

For any given program and any given constituent processor, it is possible to compute a sampling period bound for the SSIMD realization [1]. This *SSIMD bound* for programs is equivalent to the iteration period bound for fully specified flow graphs. Hence, if a program can be generated such that the SSIMD bound is equal to the iteration period bound, then the SSIMD realization is rate-optimal.

The SSIMD approach to flow graph realizations is very attractive for many reasons. First, for all SSIMD realizations in which the number of processors is less than the processor bound, the implementations are perfectly efficient and the use of N processors always increases the throughput by a factor of exactly N. Second, when the SSIMD iteration period bound is equal to the iteration period bound, as is the case for many recursive digital filter structures, then there exists no multiprocessor solution using the same constituent processor which is faster or more efficient. Third, although the sample period bound concept is not involved, SSIMD realizations work equally well for nonrecursive structures. A significant and unique aspect of SSIMD solutions is that the program for a one processor solution is identical to the program for a P processor solution. The only difference is in the interprocessor communications connections. Finally, and most importantly, the all-important communications architecture for the final implementation is completely specified by the delay node structure of the flow graph. In particular, by constraining all the delay nodes to be first order, all single-time-index (one-dimensional) SSIMD solutions can be realized with a nearest-neighbor unidirectional ring. A similar result applies to two-dimensional flow graphs, [1,15-19]. However, if a more complex communications mechanism is available, then the flow graph can be defined to take advantage of it [1].

At the beginning of the current proposal period (1984), an SSIMD compiler had been demonstrated [5] which generates full multiprocessor implementations for the laboratory multiprocessor [7-8]. This compiler finds a rate-optimal SSIMD implementation, if it exists, and the best SSIMD implementation, if it does not. SSIMD implementations are always processor-optimal and communications-optimal (if they contain only first order delays). Two important points should be made concerning this SSIMD compiler. First, its application is by no means limited to the laboratory multiprocessor around which it was developed, and it can quite easily be used in top-down design systems using microprocessors, signal processing chips, or VLSI realizations. Second, and more important, is the result that if a rate-optimal SSIMD solution exists, it is very easy to find. The information available from the computation of the flow graph bounds defines so precisely the character of a rate-optimal solution that it is very simple to test whether an optimal SSIMD solution exists and to find it if it does. In contrast, finding the best sub-optimal solution is much more computationally intense. Hence we have the paradox that the most desirable optimal solutions are the easiest to find, but they may not always exist.

E. Hardware Support

From the very beginning, this work unit has maintained a philosophy of combining the theoretical developments with actual multiprocessor hardware for validation and innovation. Up until recently, the hardware system used was the laboratory multiprocessor system based on ten DEC LSI-11/2 microprocessors [7-8]. This system has proved very useful in the past, but is now really obsolete.

Based primarily on research results from this work unit, DARPA, in 1985, awarded Georgia Tech a two year project to build a small scale prototype of a DSP supercomputer. The system is called the Optimal Synchronous Cyclo-static Array, or OSCAR, and a sixteen processor prototype system was scheduled for completion in August, 1987. The OSCAR system was being built under the direction of C. J. M. Hodges, the same person who built the previous laboratory microprocessor system. Unfortunately, due to internal funding problems at DARPA, this project has been discontinued, and the OSCAR will not be completed.

Another component of the hardware environment which impacts this work unit is the development of DSP microprocessors like the TI TMS320 family, and the AT&T DSP family. At the current time, the Digital Signal Processing Laboratory at Georgia Tech is making heavy use of the TI TMS32010 processor using a board which plugs into an IBM PC [20]. Since multiple boards can be plugged into the same system, fairly powerful multiprocessors can be configured, and these have been used for some applications [21] and in a graduate level course in multiprocessing. Although the existing boards do not have the synchronous features necessary to support the output of the multiprocessor compilers, they can be easily modified to include these features. In addition, the design and construction of new boards in this class is a relatively simple task. Because of the simplicity of constructing multiprocessors in this way, and because of the extremely good cost/performance of these machines, such small scale multiprocessors must become increasingly important in the future.

RESEARCH ACCOMPLISHMENTS:

Despite the catastrophic impact of the cancellation of the OSCAR project by DARPA, the research results from this work unit during the year have been quite good.

Work on the area of multiprocessor architectures for DSP since the last major proposal has centered in six areas: the generation of cyclo-static implementations for fully specified flow graphs; the generation of systolic implementations for fully specified flow graphs; efficient SSIMD compilation procedures; the generation of fully specified flow graphs from serial specifications; the use of blocked filters for increased multiprocessor throughput; and analysis/reconstruction filter bank theory. These topics are largely included in three theses [4,22,23], two of which are complete [4,22] and one of which is near completion [23].

A.1 Cyclo-static Implementations

By far the most important research result of this period was the creation of a cyclo-static compiler for fully specified flow graphs [3-4]. This work is part of the thesis research of David Schwartz [4].

The development of the cyclo-static compiler really grew out of an attempt to understand why SSIMD and PSSIMD implementations could be rate-optimal, processor-optimal, and communications-optimal while the systolic implementations for the same algorithms could not. There are really two separate reasons for the shortcomings of systolic arrays. The first is the fact that systolic processors are static pipelines. This means that any particular operation in an algorithm is assigned to a particular processor in the systolic array, and that operation is performed by that processor on every iteration. Hence, the operations are static and only the data moves through the multiprocessor. In contrast, SSIMD, PSSIMD, and cyclo-static processors are dynamic pipelines in which both the operations and the data move through the multiprocessor. The second reason is the effect of the global transfer clock. Indeed, this global transfer clock was the basic characteristic for which systolic arrays were named, giving the whole system it's "pumping" action. There is no fundamental requirement that all the pipeline registers in the system be clocked simultaneously. There is also no reason that each processor must perform I/O on every clock cycle. In contrast, the input-output operations in SSIMD, PSSIMD, and cyclo-static implementations move in parallel, non-overlapping wavefronts (with a periodic pattern to the spacing of successive wavefronts).

Cyclo-static implementations are a new class of multiprocessor solutions which can be used for the optimal realization of iterative or recursive algorithms on synchronous multiprocessors. A processor which realizes cyclo-static implementations can be considered to be a generalization of systolic processors, wavefront array processors and SSIMD processors. Cyclo-static realizations differ in that they are provably optimal with respect to multiple criteria.

Cyclo-static implementations are a broad class of deterministically scheduled synchronous MIMD schedules which include systolic and SSIMD implementations as special cases. As previously noted, the primary feature of a cyclo-static implementation which distinguishes it from a systolic implementation is that, viewed from the reference point of a single iteration of the algorithm, a systolic implementation is static where as a cyclo-static implementation is dynamic. In overly simplistic terms, if a systolic implementation can be considered to be an array of processors in which the instructions are fixed in space and the data travels through space, then a cyclo-static implementation is one in which both the instructions and data travel through space. This extra degree of freedom in a cyclo-static implementation is very important in generating optimal realizations. As its name implies, if viewed from points in space-time separated by an appropriate period, cyclo-static implementations can be considered static.

Cyclo-static solutions can be effectively found that achieve a subset of the following optimallity criteria: *rate optimal* (maximally parallel, minimum iteration period), *processor optimal* (maximum processor efficiency), *delay optimal* (minimum throughput delay) and *adjacent communications optimal* (adjacent processor communications only). The procedure for finding solutions is a combinatorial optimization method which is efficient for typical realizations that are rate optimal. This problem was previously considered computationally intractable. In particular, previous researchers who considered optimal deterministic scheduling of flow graphs took the approach of transforming the original directed cyclic (containing loops) flow graph to a directed acyclic graph (loop free). Unfortunately the optimal solution to the acyclic graph can only fully exploit the parallelism of the original graph for a few special cases. The original aspects of this work are the direct utilization of the original cyclical graph, the concept of applying graph bounds as part of the multiprocessor compilations procedures and the introduction of a new approach to periodic scheduling.

A.2. The Generation of Systolic Implementations from FSFGs

Although systolic algorithms are not the primary topic of this research, many of the same formalisms and techniques which can be used to automatically generate cyclo-static implementations may also be used to generate systolic implementations. One of the important outputs of this research was a general method for the transformation of algorithms describable by SIFGs into equivalent systolic realizations [10-11]. Over the past several years, there has been considerable interest in systolic implementations, and a fairly large number of systolic algorithms have been published. For the most part, these algorithms have not been derived using any formal method, but rather each has been developed and presented separately, sometimes without extensive verification. The primary virtue of the method developed in this research is that it represents a rigorous and systematic procedure which, if correctly applied, always results in an error-free solution. The research showed that many of the previously published algorithms and many new algorithms can be generated by this single set of procedures.

The class of algorithms addressed by the systolic transformation procedures are all those procedures which can be described by shift-invariant flow graphs. As noted previously, this is a very broad class of algorithms which includes not only all recursive and non-recursive linear shift invariant algorithms describable by signal flow graphs, but also matrix algorithms, systems involving decimation and interpolation, bi-linear systems, and many more.

The basis for the systolic transformation method are all graph theoretic techniques. The method is generally applied in three steps. First, an interleaving (up-sampling) transformation is applied if necessary. The transformation is necessary in most recursive systems to supply the delay elements which constrain data/information flow to a maximum distance of one adjacent processor per global clock tick (non-broadcasting). Second, a "static-pipeline iteration period bound" is computed for the transformed graph. This is equivalent to the iteration period bound with the further constraint that the implementation must be static. Finally, using a knowledge of the static-pipeline iteration period bound, a set of delay transformations are performed using either a cut-set or a single source maximum (delay) path spanning tree approach. The final resulting graph is directly realizable as a pipelined/systolic realization. Very similar results have just been reported by Jover [36].

Many well known systolic algorithms have odd numbered processors operating on odd clock cycles and even numbered processors operating on even clock cycles. For these algorithms it is possible to interleave two independent data streams and process both simultaneously. Using these techniques, it is easy to show that these properties are a consequence of the two-way interleave transformation required by step one for most recursive and minimum delay solutions.

The data interleaving is a consequence of the communications constraints. For many systems there is only one data stream to be processed. For these systems, the efficiency of systolic solutions is bounded above by the reciprocal of the interleaving factor. This inefficiency can be overcome by the new formal technique for merging operations resulting in a near systolic realization that is referred to as *merged systolic* [4].

Using these graph theoretic techniques, it is very simple to derive systolic solutions. Examples of FIR filters, IIR filters of direct form I and II, lattice filters, matrix-vector multipliers, and lower triangular systems solver have been presented [11]. The matrix-vector multiply is an extension of an FIR filter and the triangular system solver is an extension of an IIR filter.

A.3. Efficient SSIMD Compilation Procedures

As previously noted in the background section, one of the primary concerns at the beginning of this research period was the relatively slow computation times when the SSIMD compiler was unable to find rate optimal implementations. The basic reason for this effect was that when optimal implementations existed, the optimallity constraints which could be applied generally resulted in an efficient compilation. The problem was that after the compiler proved that no optimal solution existed, there were no new constraints which could be applied while searching for a sub-optimal solution.

As part of the Ph.D. research of Sae Hun Lee, a new SSIMD compiler has been implemented which can efficiently compile both optimal and sub-optimal SSIMD implementations [6]. Like the previous compiler, the new SSIMD compiler takes FSFGs as input, and gives the best possible (fastest) SSIMD implementations as output. However unlike the previous compiler, the new compiler uses linked-list structures to represent and manipulate the structure of the FSFGs, rather than matrix structures.

The new compiler operates by ranking the loops of a recursive graph in order of their criticallity, with the most critical loops first. The loops are then sequentially included in the partial solution using a restartable topological sorting technique. At each stage, the partial solution is tested for rate-optimallity. If at any stage the procedure leads to a partial solution which is sub-optimal, then this constitutes a proof that no optimal solution exists. At this point, the compiler backs up and finds the lowest iteration period which is consistent with the existing partial solution. This new iteration period is used as the basis for a new optimallity definition, with a corresponding set of new 'pseudo' critical loops, and the search continues. The dynamically defined pseudo critical loops and SSIMD iteration period bounds provide the constraints necessary to limit the search space, and reduce the complexity of the compiler.

In comparison tests between the new and the old compiler, the new compiler was found to operate at about twice the rate of the old compiler on problems which have a rate-optimal SSIMD solution, and about twenty times as fast on problems which do not. Of course, these numbers are only examples because the running times are highly problem dependent.

A.4. Multiprocessor Compilation from Serial Specifications

Another set of research results, largely included in the Ph.D. thesis of work Sae Hun Lee, is the presentation of a set of techniques for the generation of optimal multiprocessor realizations from non-parallel (serial) algorithm representations. These techniques, when they are fully implemented, will form the basis of a system which takes as input a serial presentation of the algorithm to be implemented, and gives as output an optimal SSIMD, static, or balanced PSSIMD solution [6,23]. If no optimal implementation of any of these classes exists, then the full cyclo-static compiler described above can be used to find an optimal solution.

The entire compilation procedure can be divided into four separate parts: the generation of a generic flow graph (GFG) from a serial specification; the generation of a fully specified flow graph from a GFG; the generation of the simplest multiprocessor schedule which attains rate-optimallity; and the generation/specification of the communications solution. Although these four separate parts were developed to be combined into a single compiler, each is of interest in its own right.

The first part of this work deals with the problem of finding the best GFG which corresponds to a particular serially specified algorithm. The serial representation is in the form of a set of FORTRAN arithmetic statements and DO statements. The macro nodes in the GFG are in the form of the combination of any number of the same operation. The best GFG is defined as the one with the smallest number of nodes. The basic procedure is to identify the infinite loop which defines the algorithm, and to "unwind" all of the inside DO loops to form the graph.

Once a GFG is generated, the second part of the compiler converts it to a FSFG using a tree balancing technique [6,23]. The basic procedure here is to define a *generic flow graph iteration period bound*, which is a lower bound on the iteration period bounds of all FSFGs which can be generated from the GFG. Using the bound as a guide, a FSFG with the minimum possible iteration period bound is constructed.

The research has taken two separate, but related, approaches to the last two parts of the compiler. In the first approach, the compiler uses an extended version of the SSIMD compiler discussed in section A.3 to locate the simplest optimal schedule. The compiler first tries to find a rate-optimal SSIMD implementation. If the compiler proves that no such solution exists, instead of trying to find the best sub-optimal SSIMD solution, as before, it tries to find a rate-optimal static solution. If no such solution exists, it tries to find balanced PSSIMD solutions of increasing order until a rate-optimal solution is found. If no such solution exists, a full cyclo-static solution must be used [3-4]. Then, after the rate-optimal multiprocessor schedule is identified, the compiler finds the minimum pipelined and non-pipelined communications architecture which can support the solution.

In the second approach, which is still being investigated, the communications constraints are combined with the optimallity constraints, and the last two parts of the compiler are combined.

A.5. Increasing the Parallelism of Filters

Recurrence relations, such as recursive filters, specified by *fully specified flow graphs* (FSFG), have a maximum parallelism that is constrained by one or more *critical loops*. In a processor optimal implementation, adding additional processors beyond the processor bound can not improve performance. However it is possible to increase the parallelism of the problem by modifying the FSFG. Two methods to increase the parallelism of recursive filters have been developed [4] [12]. The first approach is a blocking method which is based on the block state variable form for digital filters. For the block state variable form, an upper and lower bound on the minimum possible iteration period (*iteration period bound*) of a realization was developed. In addition, the associated number of processors required to achieve a given iteration period was determined. It was also shown that for many problems the blocked form has lower computational requirements and decreased finite word effects, even when implemented on a typical sequential uniprocessor. Similar, and related, results have been reported by Hui-Hung and Messerschmitt [24-25].

The second method, the "extended Moyer's method," [26] [4] is based on transforming the transfer function of a filter to a non-minimal form. Since the method is applied to the transfer function, the method is independent of the form of the filter. An equivalent, non-minimal, transfer function can be constructed that contains only delays of order L, (z^{-L}), in the loops. If the minimal form realization had a critical loop that contained k delays, the non-minimal form contains kL delays, and therefore the iteration period bound is a factor of L smaller. This method was suggested by Bellanger [26] for cases where $L = 2^M$, and extended to the general integer case by Moyer, [26]. The results were further extended by Schwartz [4] to reformulate the solution in terms of real coefficients and analyzed in the rate bound framework.

Both methods exhibit a cost of $\underline{O}(L^2)$ processors to achieve the maximum processing rate resulting from transforming by order L. The block state variable approach asymptotically approaches ideal speedup, while the extended Moyer's method always achieves ideal speedup. However the block state variable form has better numerical properties than the untransformed system, while the extended Moyer's method has poor numerical properties with increasing block size. While neither method is ideal, depending on the problem, both are useful for small transformation orders.

A.6. Time-Frequency Representations

The final area of research was analysis/reconstruction systems based on time-frequency representations. Such systems are fundamental components of many signal analysis and signal processing systems. This work is largely from the Ph.D. thesis of Mark Smith [22,27-30]. Mark Smith himself was supported on State research funds, and not directly on this contract. However, his thesis advisor, T. P. Barnwell III, was supported by JSEP for his part in this work.

There are two main contributions which came out of this portion of the research. The first was the invention of the conjugate quadrature filter (often referred to as Smith-Barnwell filters by other authors). These filters form the basis of the first ever maximally decimated two-band analysis/reconstruction systems [28,30] in which filters of arbitrarily good quality could be easily designed. These filters have been widely recognized as the solution to a long standing fundamental problem in digital signal processing. Multiband exactly reconstructing analysis/synthesis systems can be easily constructed using tree structures of conjugate quadrature filters.

The second major contribution in this area is the introduction of the alias-component matrix (AC-matrix) [28,31] formulation for the description of maximally decimated analysis/reconstruction systems. This formulation is based on the general filter bank transform (GFBT), which is a time-frequency representation which is similar to, but more general than, the short-time Fourier transform (STFT). The primary virtue of the AC-matrix formulation is that it allows most of the fundamental issues in maximally decimated time-frequency systems (filter quality, system complexity, frequency distortion, phase distortion, and aliasing) to be addressed separately in the design process. The effect of the AC-matrix formulation is to bring all previous maximally decimated analysis/reconstruction systems and many new systems under the umbrella of a single formalism. As such, all these related systems can be easily compared, and new systems can be easily designed.

During the last half of 1986, this work has been expanded by a new Ph.D. student named Kambis Nayebi [37]. One of the central unsolved problems in this area is to find techniques for design of high quality filter banks for analysis/reconstruction systems based on large numbers of channels. Nayebi [37] has been able to develop a set of orthogonallity constraints between the coefficients of the filters in the filter banks. This represents a powerful new tool for the realization of such systems.

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PUBLICATIONS:

Theses

1. Sae Hun Lee, "A unified approach to optimal multiprocessor implementations from non-parallel algorithm specifications," Ph.D. Thesis, Georgia Institute of Technology, October, 1986.

Journal Articles (published or accepted)

1. M. J. T. Smith and T. P. Barnwell, III, "Exact reconstruction techniques for tree-structured subband coders," *IEEE Transactions on ASSP*, June, 1986.

2. M. J. T. Smith and Thomas P. Barnwell, III, "A new filter bank theory for time-frequency representation," *IEEE Transactions on ASSP*, March, 1987.

Papers in Conference Proceedings

1. D. A. Schwartz, T. P. Barnwell, III and C. J. M. Hodges, "The optimal synchronous cyclo-static array: A multiprocessor supercomputer for digital signal processing," *1986 International Conference on Acoustics, Speech, and Signal Processing*, Tokyo, Japan, April, 1986.

2. S. H. Lee and T. P. Barnwell, III, "A topological sorting and loop cleansing algorithm for a constrained MIMD compiler of shift-invariant flow graphs," *1986 International Conference on Acoustics, Speech, and Signal Processing*, Tokyo, Japan, April, 1986.

3. T. P. Barnwell III, "Algorithm development and multiprocessing issues for DSP chips," *SpeechTec '87*, New York, NY, April, 1986.

4. T. P. Barnwell III and D. A. Schwartz, "Cyclo-static solutions: optimal multiprocessor realization of recursive algorithms," *Proc. of 1986 ASSP Workshop on VLSI and Signal Processing*, Los Angeles, CA, November, 1096.

Papers Submitted (for Journal Articles or Conference Proceedings)

1. K. Nayebi, T. P. Barnwell III, and M. J. T. Smith, "Time domain conditions for exact reconstruction in analysis/synthesis systems based on maximally decimated filter banks," *1987 Southeast Symposium on System Theory*, Clemson, SC, March, 1987.

2. S. J. A. McGrath, T. P. Barnwell III, and D. A. Schwartz, "A WE-DSP32 based, low-cost, high-performance, synchronous multiprocessor for cyclo-static implementations," *1987 International Conference on Acoustics, Speech, and Signal Processing*, Dallas, Texas, April, 1987.

WORK UNIT NUMBER 3

TITLE:

Two-Dimensional Optical Storage and Processing

SENIOR PRINCIPAL INVESTIGATOR:

T. K. Gaylord, Regents' Professor

SCIENTIFIC PERSONNEL:

E. I. Verriest, Associate Professor
J. A. Buck, Assistant Professor
E. N. Glytsis, Graduate Research Assistant (Ph.D. candidate)
A. Knoesen, Graduate Research Assistant (Ph.D. candidate)
T. A. Maldonado, A.R.O. Fellow (Ph.D. candidate)
R. S. Weis, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long-term scientific objective of this research is to develop broadly-based, theoretical and experimental knowledge of two-dimensional optical information processing including algorithms, architectures, systems, and devices. This would bring together a range of concepts from basic physics to information processing in its most generalized form. Optical systems based on content-addressable memory processing, associative processing, Givens rotations, and hyperbolic rotations are being analyzed starting from basic physical principles and extending through experimental systems performance.

RESEARCH ACCOMPLISHMENTS:

A. Complexity of Residue Number System Processing

An analytic expression for the lower bound on the complexity of residue addition and multiplication was developed Significant reduction of the the required stored logic in a content-addressable memory is noted. Errors in these results as published by C. A. Papachristou were corrected.

This research was published in *IEEE Transactions on Computers.*

B. Multi-Level Coded Residue-Based Content-Addressable-Memory Optical Computing

The extension of truth-table look-up processing beyond primitive operations (such as addition) to higher-level operations (such as discrete matched filtering) was presented. Use of the residue system and logical minimization techniques to reduce the required number of reference patterns stored in a content-addressable memory was illustrated for

16-bit full-precision addition. Multilevel coding of the numbers was introduced as a method to achieve further truth-table reduction. The required number of reference patterns for implementing the residue addition and multiplication operations were provided for all moduli from 2 through 32 with 2-, 3-, and 5-level coding. An optical holographic implementation of a system that processes multilevel coded numbers was presented.

This research was published in *Applied Optics*.

C. Truth-Table Look-Up Processing

The need for ultra-high-speed computing for a variety of modern processing problems has generated new interest in using truth-table look-up techniques. Further, due to the frequently parallel nature of these processing problems, optical systems appear to be promising for these applications. The basic principles of truth-table look-up processing were reviewed. The issues of number representation, multilevel coding, and logical minimization were developed. Example fixed-radix and residue number representations were given with and without multilevel coding. Logical reduction techniques were discussed with examples. A comparison of the number of truth-table entries needed for 16-bit full precision addition and multiplication were given, illustrating the advantage of the multi-level coded residue number representation.

These results were published in an invited paper in *Optical Engineering*.

D. Integrated-Optical Givens Rotation Device

The Givens rotation operation occupies a central role in linear algebraic signal processing. An integrated-optical coherent implementation of an elementary rotation matrix device, based on thick grating diffraction, to perform this operation was suggested. It was shown that existing electrooptic phase shifting and grating diffraction devices can be combined to produce a very fast Givens rotation device.

This research was published in *Applied Optics*.

E. Logical Minimization of Multilevel-Coded Functions

Discrete numerical values in digital processing systems may be encoded in two-level (binary) or higher-level (multilevel) representations. Multilevel coding can produce smaller and more efficient processors. In truth-table look-up processing, the number of entries (reference patterns) can be reduced using multilevel coding. Since parallel-input/parallel output optical truth-table look-up processors can be constructed based on holographic content-addressable memories, it is essential to know the minimum storage required to implement various functions. A new simple method for reducing multivalued functions was developed. This method is based on an extension of the Quine-McCluskey minimization method used for binary logic functions. This minimization method was then applied to the truth tables representing (1) modified signed-digit addition, (2) residue addition, and (3) residue multiplication. A programmable logic array gate configuration for the modified signed-digit adder was presented.

This research was published in *Applied Optics*.

F. *Grating Diffraction*

A rigorous coupled-wave analysis for metallic surface-relief gratings was presented. This approach allows an arbitrary complex permittivity to be used for the material and thus avoids the infinite conductivity (perfect conductor) approximation. Both TE and TM polarizations and arbitrary angles of incidence are treated. Diffraction characteristics for rectangular-groove gold gratings with equal groove and ridge widths were presented for freespace wavelengths of 0.5, 1.0, and 10.0 microns for all diffracted orders as a function of period, groove depth, polarization, and angle of incidence. Results included the following: (1) TM polarization diffraction characteristics vary more rapidly than do those for TE polarization, (2) 95% first-order diffraction efficiency occurs for TM polarization at 10.0 microns, (3) <0.1% zero-order specular reflectivity occurs for both TE and TM polarizations, (4) >50% absorption of incident power occurs at 0.5 micron, and (5) the perfect-conductor approximation is not valid for TM polarization at any of the wavelengths and is not valid for TE polarization at 0.5 micron.

This research was published in *Journal of the Optical Society of America.*

G. *Analysis Interdigitated Electrodes on Electro-Optic Waveguides*

Integrated optical interdigitated-electrode devices are used to diffract light and to launch acoustic waves. The electric field and the permittivity and strain tensors induced by a voltage applied to periodic interdigitated electrodes of finite thickness on the surface of an anisotropic electro-optic crystalline waveguide were calculated rigorously. The extremely important existence of a buffer layer between the electrodes and the waveguide occurring in practical devices was included in the analysis.

This work has been accepted for publication in *Journal of Lightwave Technology.*

H. *Zero-Reflectivity Dielectric Surface Relief Gratings*

Using rigorous coupled-wave analysis, high spatial-frequency rectangular-groove surface-relief phase gratings were shown to be capable of exhibiting zero reflectivity. Thus these corrugated surfaces may act as antireflection coatings in a variety of applications. The diffraction characteristics of rectangular-groove surface-relief gratings were presented for several ratios of incident wavelength to grating period as a function of filling factor, groove depth, angle of incidence, and polarization. The conditions for zero reflectivity were identified. Results are compared to single-homogeneous-layer approximate theory results. In the limit of long wavelengths for an electromagnetic wave in a dielectric of refractive index n_1 normally incident upon a dielectric of index n_2, it was determined that for antireflection behavior, the grating groove depth should be $\lambda/4(n_1 n_2)^{1/2}$ and the filling factor should be $n_1/(n_1 + n_2)$ or $n_2/(n_1 + n_2)$ for the electric field perpendicular or parallel to the grating vector, respectively. The spectral and angular responses of these gratings are like those of single-homogeneous-layer antireflection coatings. These gratings also exhibit birefringent retardation.

This research has been accepted for publication in *Applied Optics.*

PUBLICATIONS:

Journal Articles (Published or Accepted):

1. Mirsalehi, M. M. and Gaylord, T. K., "Comments on direct implementation of discrete and residue-based functions via optimal encoding: A programmable array logic approach," *IEEE Transactions on Computers*, vol. C-35, pp. 829-830, September 1986.

2. Mirsalehi, M. M. and Gaylord, T. K., "Multi-level coded residue-based content-addressable-memory optical computing," *Applied Optics*, vol. 25, pp. 2277-2283, July 15, 1986.

3. Gaylord, T. K. and Mirsalehi, M. M., "Truth-table look-up processing: Number representation, multi-level coding, and logical minimization," *Optical Engineering*, vol. 25, pp. 22-28, January 1986. (invited).

4. Mirsalehi, M. M., Gaylord, T. K., and Verriest, E. I., "Integrated optical Givens rotation device," *Applied Optics*, vol. 25, pp. 1608-1614, May 15, 1986.

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6. Moharam, M. G. and Gaylord, T. K., "Rigorous coupled-wave analysis of metallic surface-relief gratings," *Journal of the Optical Society of America A*, vol. 3, pp. 1780-1787, November 1986.

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8. Glytsis, E. N., Gaylord, T. K., and Moharam, M. G., "Electric field, permittivity, and strain distributions induced by interdigitated electrodes on electro-optic waveguides," *Journal of Lightwave Technology*, vol. LT-5, 1987, (accepted).

9. Mirsalehi, M. M. and Gaylord, T. K., "Residue number systems in content-addressable memory processing," *Proc. S.P.I.E.*, vol. 752, 1987, (accepted).

10. Gaylord, T. K. and Verriest, E. I., "Matrix triangularization using arrays of integrated Givens rotation devices," *Computer*, vol. 20, 1987, (invited).

Interactions and Technology Transfer

Analysis of allowed hybrid modes in anisotropic waveguides and interdigitated-electrode produced electric fields in integrated optical anisotropic waveguides is being performed for the US Armament Engineering and Development Center in Dover, New Jersey.

Honors and Awards

Thomas K. Gaylord received "Outstanding Contribution in Research" award for the paper "Analysis and applications of optical diffraction by gratings" given by the Southeastern Section of the ASEE, 1986.

Thomas K. Gaylord received "Best Research Paper in Engineering" award for paper "Analysis and applications of optical diffraction by gratings" from Sigma Xi, 1986.

WORK UNIT NUMBER 4

TITLE:

Two-Dimensional Optical/Electronic Signal Processing

SENIOR PRINCIPAL INVESTIGATOR:

W.T. Rhodes, Professor

SCIENTIFIC PERSONNEL:

J.N. Hereford, Graduate Research Assistant (Ph.D. candidate)
R.W. Stroud, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to gain a good understanding of the capabilities and limitations of hybrid optical/electronic methods for high throughput processing of 2-D signal information and to develop new and widely applicable techniques based on such methods. Emphasis is placed on establishing the capabilities of systems that mate well with digital signal processing systems.

RESEARCH ACCOMPLISHMENTS:

A. Bipolar Incoherent Spatial Filtering

Our original objective in this area was to develop effective methods for bipolar spatial filtering using incoherent optical systems that are simple to implement and efficient with respect to light utilization. That objective was augmented with the additional goal of maximizing overall system dynamic range in the case where optical and digital subsystems are combined with a scanning operation in between.

Work in 1985 saw completion of an elegant unifying theory of pupil function specification for the two kinds of two-pupil hybrid optical/electronic spatial filtering methods (one method involving interference of light from the two pupils, the other method not). Further, a two-step algorithm was developed for designing pupil functions that are optimal or nearly so in the sense of reducing noise and enhancing contrast. During the current year, three journal articles on the research have been published, a manuscript for another paper has been submitted for publication, and a paper on the subject was also presented at a conference.

Currently a new doctoral student is looking at a scheme for realizing pupil function syntheses of this kind using birefringent materials in common-path-interferometer-based imaging systems. This approach promises to eliminate many of the practical difficulties characteristic of other interferometer-based systems.

B. Optical Implementation of Morphological Transformations

In late 1985 we began a new study of highspeed opto-electronic methods for implementing morphological transformations (e.g., erosions, dilations, openings, closings) on binary images and nonlinear filtering operations (e.g., median filtering) on gray-scale images. The morphological transformations, which involve the interaction of the shape under study with a structuring element, are being used more and more in pattern recognition and artificial intelligence for robotic vision. Some of these operations are quickly performed using binary digital logic circuitry. Others, however (e.g., skeleton decomposition, where the pattern under study is reduced to primitive structural components), are sufficiently complex that TV-frame-rate processing is difficult to achieve. The schemes investigated perform the necessary operations in parallel. Real-time operation is contingent on finding a device that, much like high contrast film, will perform a hard limiting operation on an image, but essentially instantaneously. Such devices are currently under development (e.g., at GTE laboratories), and the methods being investigated appear to have good potential for success in a real-time environment.

In the processing operation, a binary input pattern is presented to a shift-invariant imaging system and a blurring operation performed. The blur function, which plays the role of the structuring element in the transformation, is often a disk, though other shapes are easily accommodated. The resulting blurred image is then hard limited. If the threshold is set for a high intensity, an erosion results; with a low intensity threshold, a dilation results. Setting the threshold at the 50% level results (with binary input and blur functions) in a median operation. Other threshold levels can be used to obtain other rank-order processing operations, assuming the input and blur functions are binary. These simple operations have been successfully demonstrated, and results have been presented at a conference. A journal publication is in preparation.

Continuing work in this area centers on further development of these opto-electronic methods and their extension to (a) skeleton decomposition of binary images and (b) nonlinear filtering (e.g., median filtering) of gray scale images. We have worked out conceptually a method for skeleton decomposition that involves integrating the results of a number of erosions followed by implementation of a Laplacian or similar operation and a hard limiting. All operations can be performed opto-electronically in parallel. A method for nonlinear processing of gray scale images has also been worked out and is under experimental investigation.

C. Other Image Processing Research

Quasi Space-Invariant Imaging. Contrary to widespread belief, a single-lens imaging system with limiting aperture in the lens plane is not space-invariant for coherent imaging and cannot, therefore, be described by a convolutional input-output relationship. Recently we conducted an experimental verification of a new principle of quasi space-invariance that applies to the intensity transmittance of diffuse, coherently illuminated objects imaged with what would normally be a space-variant single-lens imaging system. A brief manuscript presenting the principle is in preparation. The quasi space-invariance arises because of the whitening of the object spectrum introduced by the diffuser. Because of this whitening, all regions of the object "see" the same effective transfer function rather than substantially different ones. The principle is primarily of academic interest because of the speckle that is introduced in the image.

Coherent Optical Processing of Incoherently Illuminated Objects. Normally it is not possible to perform classical coherent spatial filtering operations like phase-contrast and dark-field imaging on objects that are illuminated incoherently (e.g., by light from a spatially extended incoherent source). We have recently discovered a new method by which, under a limited set of conditions, it is indeed possible to do coherent spatial filtering on incoherently-illuminated objects. The idea was first considered in the context of phase-contrast imaging of thermal plumes from submarines illuminated by noise from ocean waves. Our extension is to the optical case. A key restriction is that the object be only weakly diffracting, such as a weak phase object. We are preparing to verify the concept experimentally.

Falling Raster/Folded Spectrum Relationships. We, along with a small number of other researchers (e.g., William Stoner, Harper Whitehouse, Terry Turpin), have known for some time that alternatives exist to the conventionally-employed falling raster format for performing 2-D spectrum analysis on 1-D signal information. However, these alternatives have never been modeled analytically. During the past quarter a new doctoral student has begun the task of detailing the basic relationships between the non-conventional recording formats and the corresponding 2-D "folding" of the signal spectral distributions. It is not yet clear what kind of payoff we can expect from this study, though the resulting increased flexibility in recording format may be of use in some high-speed spectral analysis applications.

Low-Signal-to-Bias-Ratio Optical Signal Processing. Work that began under this program in connection with a Fourier transform scanning hybrid image processing system has evolved to center on the general problem area of bias buildup, signal-to-bias ratio, and signal-to-noise ratio in time-integration optical processing. This is a generic problem that affects several important classes of optical signal processing, including time-integration acousto-optic processing of radar and communication signals and incoherent holography.

We have begun a conceptual consolidation, with respect to bias problems, of previous work in the areas of time-integration optical signal processing, incoherent holography, and multiple-exposure holography and are developing an analytical formulation of the general problem applicable to these three areas. A method has been found and reported for optimizing small signal-to-bias-ratio exposures for time-integration optical processing where bleached silver-halide recording materials are used as the detector. Analytical details were reported at a recent conference. We are currently conducting experimental verification. Assuming our analytical results are confirmed, we shall submit a manuscript for Journal publication.

PUBLICATIONS:

Journal Articles (published or accepted)

1. Mait, Joseph N. and Rhodes, William T., "Two-pupil synthesis of optical transfer functions: 2-pupil function relationships," *Applied Optics*, Vol. 25 (15 June 1986), pp. 2003-2007.

2. Mait, Joseph N., "Existence conditions for two-pupil synthesis of bipolar incoherent point-spread functions," *Journal of the Optical Society of America A*, Vol. 3 (April 1986), pp. 437-445.

3. Mait, Joseph N., "Pupil-function design for bipolar incoherent spatial filtering," *Journal of the Optical Society of America A*, Vol. 3 (April 1986), pp. 1826-1832.

Papers in Conference Proceedings

1. Mait, Joseph N., "Existence and synthesis of bipolar incoherent pointspread functions," in *Signal Recovery & Synthesis II*, Technical Digest of Optical Optical Society of America Topical Meeting, April 1986, Honolulu, pp. 27-30.

2. O'Neill, Kirt S. and Rhodes, William T., "Morphological Transformations by Hybrid Optical-Electronic Methods," in *Hybrid Image Processing*, D. Casasent and A. Tescher, eds. (Proc. SPIE, vol. 638, 1986), pp. 41-44.

3. Rhodes, William T., Stroud, Robert, and Gaynor, Edwin S., "Maximizing Diffraction Efficiency of Bleached Time-Integration-Exposure Silver-Halide Holograms," in *Holography Technical Digest* (Optical Society of America, 1986), pp. 96-99.

Papers Submitted (for Journal Articles or Conference Proceedings)

1. Mait, Joseph N. and Rhodes, William T., "A pupil function design algorithm for bipolar incoherent spatial filtering," submitted to *Applied Optics*.

Interactions with DoD Labs

Met with Dr. Al Ellinthorpe of DARPA/STO on 30 May 1986.

Met with Dr. John Lee at the Naval Research Laboratory, 13 August 1986.

Met with P. Denzil Stilwell and Dr. John Lee at the Naval Research Laboratory, 23-25 September 1986.

Met with Dr. Jacques Ludman of RADC/Hanscom Field on 18 December 1986.

WORK UNIT NUMBER 5

TITLE:

Optimal Multiprocessor Structures for the Implementation of Digital Signal Processing algorithms on High Density Integrated Circuits

SENIOR PRINCIPAL INVESTIGATORS:

D. A. Schwartz, Assistant Professor and J. H. Schlag, Professor

SCIENTIFIC PERSONNEL:

H. Forren, (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

To develop techniques for the automatic generation of optimal or highly efficient implementations of digital signal processing algorithms for synchronous multiprocessor VLSI architectures.

RESEARCH ACCOMPLISHMENTS:

A. Generalization/Extension of Cyclo-Static Scheduling

Work performed in conjunction with H. Forren, a research assistant, has yielded generalizations and extensions to cyclo-static scheduling as well a rudimentary proposal for a basic VLSI processor node.

The method of cyclo-static scheduling has been generalized or extended in the following areas: 1) inhomogeneous processors; 2) pipelined processing elements; 3) hierarchical nodes; 5) a communications bound; and 6) Gantt chart permutations.

Previously only homogeneous processors were considered. For many DSP problems such as filtering, only the atomic operations of multiplication and addition are needed. When the processing elements are restricted to homogeneous processors even though processor utilization may be optimal, the system efficiency is lower since the processor must be capable of both multiplying and adding. This usually implies that the utilization within the processor node is sub-optimal. This is particularly important when considering algorithmically specialized (custom) processors in the VLSI context. For efficient utilization of silicon area a design based on simple multiplier and adder elements is more effective than a general purpose processor that must include complex control and storage and ALU. The previously reported lower bound on the number of processors can be directly extended by partitioning operations into a set of operations associated with each processor type. This can also be used to model inhomogeneous communications delay since the model normally binds communication delay to the producing operator.

Pipelined processing elements are attractive at both the discrete and VLSI element level. This is because pipelining usually yields the lowest cost approach to concurrency. Pipelined processor elements can also be handled by a minor extension to the previously reported bounds. The iteration period bound and the delay bound are now computed in terms of the pipeline latency instead of the operational latency. Other expressions such as those for the processor lower bound and for the processor modulo constraint must use the stage latency. While the extensions are very simple, they are also very powerful and, in addition, have been successfully applied as a tool for writing optimal code for pipelined array processors and pipelined DSP chips.

Hierarchical graphs can be used to reduce the apparent complexity of the graph to the point where the optimization tools are effective. Further modifications of previous expressions must be made in order to allow the use of hierarchical nodes. Instead of associating a single latency with the time from the arrival of the last input to the appearance of the single output, an independent latency must be associated with each input or output (where multiple outputs must be considered as well).

A new bound on communications has been determined. This communications bound reflects the local characteristics of a homogeneous communications network required to implement a signal flowgraph. The number of neighbors with which a processor can directly communicate (including itself) is an important measure of network complexity. By observing the worst case fan-in or worst case fan-out of a signal flowgraph, as well as the pad time allowed along the respective branches, the direct neighbor lower bound can be established.

In prior work, only adjacent processor communications were considered in scheduling and mapping a solution onto a target. For an architecture that supports parallel communications and operations it is practical to pass data through more than one processor when the schedule has sufficient slack time between the availability of the data and the need to use it. From a valid schedule, the exact communication requirements of that schedule may be found directly. Simple formulas indicate the number of communication steps available for data to travel from one processor to another. The distance between these processors in terms of a network model is similarly found. If all chords of a network (if any) are shorter than this specification, the data can not travel far enough in the time allowed. Defining the local radius of the network to be the greatest distance that data can travel in one communications step simplifies the process of determining a valid (if it exists) processor mapping given a schedule. These preliminary results may form the basis of an effective scheduler that can determine the minimum possible communications support for a given FSFG/algorithm.

The Gantt Chart has been presented as a useful representation of a schedule or program. Numerous manipulations to the Gantt Chart allow one schedule or program to be transformed into another trivially different one. In the case of the program, a dramatic difference in the communications network may result. A brief list of manipulations is presented here.

Columns may be arbitrarily rotated, effecting only a relative time shift.
Rows may be arbitrarily switched, effecting which processor does which row.
Row fragments may be sliced and spliced so long as there is no time shift.
Any two (or all) cycles may be spliced into a single cycle.

An important result of manipulating Gantt Charts is the ability to transform any schedule or program into SSIMD form with homogeneous processors. The homogeneous processor requirement is obvious for SSIMD. If inhomogeneous processors are required, then cycles may be spliced until a single cycle exists for each type of operation or processor. If the number of rows in each cycle is the same, then the result is a PSSIMD solution. If the number of rows in any two cycles differ, then the result is a *multiple cyclo-static instruction streams, multiple data streams* (MCIMD) solution. [MCIMD is an extension of cyclo-static to allow multiple lattice vectors, which are often necessary for inhomogeneous solutions].

The subject of the following section is the result of work performed in conjunction with P. W. Hutto, a graduate student. Hutto was supported by with funds from DARPA and the State of Georgia (E-Funds). His advisor, D. A. Schwartz was supported in this research by JSEP. Progress and preliminary results has been made in the following areas.

B. Optimal Data Routing

Based on the theoretical properties of cyclo-static realizations, DARPA sponsored the design of a small scale model of a super computer for digital signal processing which is referred to as OSCAR (Optimal Synchronous Cyclo-static ARray). OSCAR features a generalized/extended ILLIAC-IV type interconnection network. The ILLIAC-IV interconnection network was a simple SIMD machine that required each node to execute the identical routing instruction. OSCAR allows independent, arbitrary, five port interconnection at each node. In addition the interconnection network operates in parallel with processor node computations. This powerful interconnection network is the backbone of OSCAR's fine grain parallelism. However, for those algorithms of interest that do not meet the model (cyclo-static) of the existing compiler tools (e.g. FFT), the problem of optimal data routing for implementations where data must be passed through one or more processor nodes to reach its destination is largely unsolved. Recent research has only addressed hypercube routing and restricted cases of ILLIAC-IV type meshes.

Spurred by problems in determining an optimal routing algorithm for a parallel FFT, a software testbed was developed to investigate optimal routing for generalized many-to-many data permutations. An optimization technique based on simulated annealing was developed to determine optimal/near optimal routes. The method is based on assigning minimum length paths to all data paths, then annealing the paths by introducing delays and path permutations so as to eliminate all communications conflicts.

Preliminary results indicate that the method is very efficient at producing optimal/near optimal data routes. The viability of the the simulated annealing technique was suggested by the success of the method for optimizing layout routes for VLSI.

C. Differential Equation Compiler

The numerical solution to differential equations is a very common, CPU intensive application of scientific computing. In particular there has been great interest in the real time solution of the equations of motion for robot arms. It was noted that the solution to initial value problems that do not use data-adaptive integration techniques are precisely the class of problems that can be optimally solved with cyclo-static techniques. However the resulting FSFG's are complex and irregular. To provide a more effective environment a simple compiler was developed to demonstrate the feasibility of using a high level, FORTRAN-like, language to specify the systems of differential equations. The output of the compiler is a list that specifies the resulting FSFG. The current implementation is rather frail and needs to be strengthened to solve a larger class of equations, and to use more advanced solution techniques. This was only intended as a feasibility study and it is not planned to pursue this area further at this time.

D. Off Chip Interface Issues

As a result of developing the OSCAR architecture several results were discovered relating to communications design and off-chip interfaces in fine grain parallel architectures. It is unlikely that it will be possible to implement a high performance multiprocessor system on a single chip in the near future. Therefore the off chip interface is crucial in the design process. There is always a large speed penalty for going off chip. In the cyclo-static multiprocessor model it had been assumed that the interchip delay was negligible compared to the intrachip computation time (for an atomic operation). During the course of the past three years this has changed significantly.

Two methods have been developed to handle this problem. First, if the interchip delay is comparable and less than (or equal to) the operational delay, then the interchip communications time can be effectively pipelined by using an interleaved design. This allows all communications to be treated homogeneously and maximizes the system throughput. The penalties are that this requires partitioning (or cooperation) of system resources between the tasks, the existence of orthogonal tasks, increased throughput delay, and potential problems with synchronizing tasks.

The second method is to treat the interchip vs. intrachip communications as an inhomogeneous communications medium. In the cyclo-static system model it may be possible to assign all operations in a critical loop to a single chip and to split non-recursive sections and non-critical loops with sufficient slack time across chip boundaries by spending the slack time on the communications delay. Simple examples have demonstrated the feasibility of this approach, however a formal method to handle inhomogeneous communications is in the early stages of development and will require future work.

Both methods seem to indicate that for technologies such as GaAs where the ratio of interchip to intrachip delay is so large that fine grain parallelism across chip boundaries is impractical. This suggests a hierarchical approach of fine grain parallelism for intrachip scheduling and medium to coarse grain parallelism for interchip scheduling.

A second issue, closely related to the previous issue is communication bandwidth. To achieve fine grain parallelism a very large communications bandwidth is required. Consider the case of all atomic operations being simple binary operators (two inputs, one output). For each operation, potentially, two operands must be fetched from other processor elements. If the communications time is to be negligible compared to the computation time this implies approximately an order of magnitude more communications bandwidth then used in conventional design wisdom. In order to make it practical to find optimal/good schedules, at present it is necessary to insure that the communications is non-blocking. This can only be achieved by supporting an even higher communications bandwidth (which is a function of the algorithm and the target communications network). This does not imply that fine grain parallelism is flawed. What is does imply is that for a system to be able to solve a class of problems efficiently with large parallelism that there is a need for large communications bandwidth.

In short, powerful, high bandwidth communications is fundamental to fine grain parallelism. Much more work needs to done on the fundamental architectual implications of communications requirements on the off chip interface. It is also obvious that fine grain parallelism carries with it architectual complexities that may be better addressed by applying the fine grain approach and theory on a coarser grain (herein lies current applicability).

PUBLICATIONS:

Books or Chapters in Books

1. Schwartz, D. A., and Barnwell, T. P., III, "Cyclo-Static Solutions: Optimal Multiprocessor Realizations of Recursive Algorithms," Chapter 11, Editors S. Y. Kung, R. E. Owen and J. G. Nash, *VLSI Signal Processing II*, IEEE Press, N. J., 1986 (originally presented at the 1986 IEEE ASSP Workshop on VLSI Signal Processing, Nov. 1986, Los Angeles, California).

Papers in Conference Proceedings

1. Schwartz, D. A. and Barnwell, T. P., III, "The Optimal Synchronous Cyclo-Static Array: A Multiprocessor Supercomputer for Digital Signal Processing," *Proc. of the International Conference on Acoustics, Speech and Signal Processing*, Tokyo, Japan, April 1986.

2. Forren, H. F. and Schwartz, D. A., "Transforming Periodic Synchronous Multiprocessor Programs," *(submitted to) Proc. of the International Conference on Acoustics, Speech and Signal Processing*, Dallas, TX, April, 1987.

3. McGrath, S. J. A., Barnwell, T. P., III, and Schwartz, D. A., "A WE-DSP-32 Based, Low Cost Multiprocessors for Cyclo-Static Implementations," *(submitted to) Proc. of the International Conference on Acoustics, Speech and Signal Processing*, Dallas, TX, April, 1987.

WORK UNIT NUMBER 6

TITLE:

Electromagnetic Measurements in the Time and Frequency Domains

SENIOR PRINCIPAL INVESTIGATOR:

G. S. Smith, Professor

SCIENTIFIC PERSONNEL:

W. R. Scott, Jr., Assistant Professor
M. Gouker, Graduate Research Assistant (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The broad objective of this research is to develop new methodology for making electromagnetic measurements directly in the time domain or over a wide bandwidth in the frequency domain. This research includes the development of the theoretical analyses necessary to support the measurement techniques. One aspect of the research is the systematic study of radiating structures placed near or embedded in material bodies. In a practical situation, the radiator might serve as a diagnostic tool for determining the geometry, composition or electrical constitutive parameters of the body.

RESEARCH ACCOMPLISHMENTS:

During the last year, research was initiated on the following new topics.

A. Pulse Excited Antennas Near a Material Interface

Ground penetrating radar systems have been proposed for many applications; these include the detection of mines and buried unexploded ordinance, the location of buried utilities and the mapping of subsurface geological structure. The systems generally make use of a temporarily short, wide bandwidth, pulse. The pulse is transmitted and received by one or more antennas located above the surface of the earth.

The characterization and design of antennas for this application are complicated by two factors: the broad-band requirements and the effect of the air/earth interface on the performance of the antenna. Two types of antennas have generally been used for systems of this kind: dipole type antennas located very close to the air/earth interface and TEM horn antennas located at a larger distance from the air/earth interface.

We have initiated a research program to study new antennas for this application. Experimental facilities were constructed for measuring the performance of antennas over an interface between air and wet sand. Sensors and targets embedded in the sand are used to evaluate the field of the antenna.

Scale model antennas are used with this system; full size antennas would generally require larger test facilities than can be accommodated in our laboratory. Techniques have been developed for correcting errors in the automated time-domain instrumentation used with this system.

B. Materials for Electromagnetic Scale Models

Electromagnetic scale models are of value in the design and testing of electromagnetic systems that are on a scale too large or too small for routine laboratory use. For example, the performance of antennas over or buried in the earth can be evaluated in the laboratory using reduced size scale models operated at frequencies higher than those used for the actual antennas. For this model, a material is needed that will model the electrical properties of the earth. Scale models with increased size are also used. A microscopic antenna on a substrate may be modeled by a larger antenna operated at a frequency lower than that for the actual antenna. A material is then needed that can model the electrical properties of the substrate.

Clearly it is desirable to have a series of materials with a range of electrical properties or mixtures of materials with adjustable electrical properties for use in scale models. We are beginning a study of the electrical properties of emulsions (mixtures of oil and water) as binary solutions with adjustable electrical properties. The constituents of the emulsion are relatively inert and satisfy all of the requirements as to toxicity, flammability, etc. We started a systematic investigation of the electrical properties of several emulsions, with the objective of obtaining information on:

a. the range of electrical parameters that can be realized,

b. The frequency dependence of the electrical properties,

c. the accuracy of mixing formulas for predicting the electrical properties,

d. the stability of the emulsions.

PUBLICATIONS:

Journal Articles (published or accepted)

1. Scott, W. R., Jr., and Smith, G. S., "Error analysis for dielectric spectroscopy using shielded open-circuited coaxial lines of general length," *IEEE Trans. Instrumentation and Measurements*, Vol. IM-35, pp. 130-137, June 1986.

2. Scott, W. R., Jr., and Smith, G. S., "Dielectric spectroscopy using monopole antennas of general electrical length," *IEEE Trans. Antennas and Propagation*, Vol. AP-34, pp. 919-929, July 1986.

3. Scott, W. R., Jr., and Smith, G. S., "Error corrections for an automated time-domain network analyzer," *IEEE Trans. Instrumentation and Measurements*, Vol. IM-35, pp. 300-303, September 1986.

4. Smith, G. S., and Scott, W. R., Jr., "Measurement of the electrical constitutive parameters of materials using antennas, Part II," *submitted to IEEE Trans. Antennas and Propagation.*

Papers in Conference Proceedings

1. Scott, W. R., Jr., and Smith, G. S., "Dielectric spectroscopy using monopole antennas of general electrical length," 1986 International IEEE Antennas and Propagation Symposium, Philadelphia, PA, June 1986.

Interaction with DoD Labs

During the period of the contract, a study entitled "Hardened Antenna Technology Assessment" was performed for the Air Force (RADC, Griffis AFB). This study made use of information developed on the Joint Services Electronics Program.

WORK UNIT NUMBER 7

TITLE:

Automated Radiation Measurements for Near- and Far-Field Transformations

SENIOR PRINCIPAL INVESTIGATOR:

E. B. Joy, Professor

SCIENTIFIC PERSONNEL:

R. E. Wilson, Graduate Research Assistant (Ph.D. Candidate)
B. Keith Rainer (Ph.D. Candidate)
Will D. Caraway (M.S. Candidate)
John R. Thomas (M.S. Candidate)
Darryll G. Wright (M.S. Candidate)
Mike G. Guler (M.S. Candidate)
Sherill J. Edwards (B.S. Candidate)

SCIENTIFIC OBJECTIVE:

The long term objective of this research is to understand the near field and far field coupling between antennas in the presence of scatterers. Special emphasis is placed on determination of limits of accuracy in the measurement of the fields radiated or scattered by an antenna-under-test by a second antenna and to develop techniques and computer algorithms for compensation of such measurements due to known geometrical or electromagnetic anomalies.

Three application areas are pursued: a) antenna measurements, where the effects of scatterers are suppressed or compensated; b) scattering measurements, where the effects of scatterers are enhanced and c) radome measurement, where the effects of the scatterer (the radome) are of equal importance to the antenna measurement.

RESEARCH ACCOMPLISHMENTS:

A. Spectral Evaluation of Reflector Surfaces Used for Compact Antenna Ranges

The test zone field quality of a compact antenna range is dependent on primarily three factors: the surface accuracy and smoothness of the range reflector, the scattering and diffraction from the edge of the reflector and the complex vector far field pattern of the feed antenna. It was shown that the effect of the surface accuracy and smoothness can be quantified using a newly developed spectral analysis technique. The surface error is expressed as a two-dimensional summation of sinusoids. The illuminating field is expressed as a two-dimensional spectrum of plane waves incident on the reflector. It is shown that the effect of the reflector surface error is to phase modulate each plane wave with a modulation index proportional to the magnitude of the sinusoidal components of the surface error. The compact range geometry was shown to be a low-pass filter, allowing only those plane waves with spatial period of approximately three wavelengths and below to pass to the quiet zone. Thus it was learned which reflector surface accuracy were important for compact range use and the relationship between surface accuracy and test zone field performance. These results were presented at the 1986 Antenna Measurement Techniques Association Workshop on Compact Ranges and presented at the 1986 Antenna Measurement Techniques Association Meeting.

B. Near-Field Measurement of Radome Performance

Initial work has been carried out to develop a technique of near-field measurements of radome performance. Spherical surface near-field measurements have been made of a fused silica, tangent ogive, missile radome at 11.75 GHz. A special antenna was designed and constructed and an existing radome was used for the measurement. A "backward transform" algorithm is concurrently under development to determine the fields on the outer surface of the radome from the measured near-field data. Backward transforming using a spherical wave expansion is both non-unique and unstable. The higher order modes, which must be allowed in the solution, increase rapidly as the radius of the back projection decreases. Preliminary results show that sufficient information is contained in the radiating modes and little is lost in setting the higher order mode amplitudes to zero. Papers describing the near-field measurements made with and without a radome and the results of the initial work on radome performance assessment using this new measurement technique were presented at the 18th Symposium on Electromagnetic Windows and the 1986 Antenna Measurement Techniques Association Meeting.

This work, plus other publications and technology transfers of the principal investigator are summarized in the following:

PUBLICATIONS:

Books or Chapters in Books

1. Joy, E. B., Paik, N., Brewer, T. E., Wilson, R. E., Webb, R. P., and Meliopoulos, A.P., "Summarized Graphical Data for Ground Grid Analysis," Appendix of the *IEEE Standard 80-1986, Guide for Safety in Substation Grounding.*

Journal Articles (published or accepted)

1. Effenberger, J. A., Strickland, R. R., and Joy, E. B., "The Effects of Rain on a Radome's Performance," *Microwave Journal*, Vol. 29, No. 5, May 1986, pp. 261-274.

Papers in Conference Proceedings

1. Cooke, W. P., , Dunn, A. G., Jameson, C. R., Joy, E. B., Montgomery, J. P., Eggers, D. S. and Tang, S. "Retrofitting a Tapered Anechoic Chamber in a Large Near-Field Measurement System," *Proceedings of the 1986 International IEEE Antennas and Propagation Symposium*, Philadelphia, PA, June 9-13, 1986.

2. Dunn, A. G., Joy, E. B., Montgomery, J. P., Eggers, P. S. and Tang, S., "Development of a Large Near-Field Measurement System for Testing Space-Borne Antennas," *Proceedings of the 1986 Antenna Measurement Techniques Association Meeting*, Ottawa, Ontario, September 23-25, 1986.

3. Joy, E. B., Wilson, R. E., Caraway, W. D., Hill, C., and Edwards, S. J., "Near Field Measurement of Radome Performance," *Proceedings of the Eighteenth Symposium on Electromagnetic Windows*, Atlanta, Georgia, September 17-19, 1986.

4. Joy, E. B., Wilson, R. E., Effenberger, J. A., Punnett, M. B., and Strickland, R., "The Electromagnetic Effects of Water on the Surface of a Radome," *Proceedings of the Eighteenth Symposium on Electromagnetic Windows*, Atlanta, Georgia, September 17-19, 1986.

5. Joy, E. B., and Wilson, R. E., "Spectral Evaluation of Reflector Surfaces Used for Compact Ranges," *Proceedings of the 1986 Antenna Measurement Techniques Association Workshop*, Philadelphia, PA, June 13, 1986.

6. Joy, E. B., and Wilson, R. E., "Spectral Evaluation of Reflector Surfaces Used for Compact Ranges," *Proceedings of the 1986 Antenna Measurement Techniques Association Meeting*, Ottawa, Canada, September 23-25, 1986.

Technology Transfer

1. U. S. Navy: M. I. T. Lincoln Laboratory is developing a high performance surveillance radar system which incorporates a shipboard mounted ultra-low sidelobe planar phased array antenna. The array has a 5-meter by 10-meter aperture and a -55 dB rms sidelobe levels. M.I.T. Lincoln Laboratory will install a multi-million dollar plane-polar near-field measurement system to test and align the phased array. To achieve the desired measurement and alignment accuracies, the K-correction probe

position error compensation technique and algorithm developed under JSEP sponsorship will be transferred to M.I.T. Lincoln Laboratory. (The request for proposal on the facility specifies use of this technique.)

2. U. S. Army Electronic Proving Ground, Fort Huachuca, Arizona: The spectral analysis technique, for the evaluation of reflector surfaces developed under JSEP sponsorship is currently being used in the design of a large outdoor compact antenna measurement range at Fort Huachuca.

ANNUAL REPORT APPENDIX
REPRINTS

Joint Services Electronics Program
DAAG29–84–K–0024
April 1, 1984 – December 31, 1984

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

JANUARY 1985

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

TECH

ANNUAL REPORT APPENDIX

Joint Services Electronics Program

DAAG29-84-K-0024

April 1, 1984 - December 31, 1984

Publications

On

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE
AND
THEORY AND APPLICATIONS OF ELECTROMAGNETIC
MEASUREMENTS

January, 1985

School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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18. SUPPLEMENTARY NOTES

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Signal Processing
Holographic Storage
Digital Filtering
Iterative Signal Restoration
Multiprocessor Architectures
Optical Processing
Time-Domain EM Measurements
EM Radiation Measurements

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is a supplement to the annual report on research under the auspices of the Joint Services Electronics Program. The supplement consists of a printed table of contents and a set of microfiche containing all papers and theses produced under this contract. Specific topics covered are: digital signal processing, parallel processing architectures, two-dimensional optical storage and processing, hybrid optical/digital signal processing, electromagnetic measurements in time domain, and automatic radiation measurements for near-field and far-field transformations.

I. Introduction

This supplement to the annual report consists of the following printed table of contents and a set of microfiche containing all papers and theses produced with JSEP support and published during the period April 1, 1984 through December 31, 1984.

This form of reporting is modelled after that introduced by the Stanford Electronics Laboratories for the same purpose. The result is a compact presentation of a large quantity of information which can be produced much more economically than printing. On the other hand, it is realized that microfiche is less convenient than a printed document. Therefore, those who are interested in particular reprints may contact R. W. Schafer to request a copy of any of the listed papers.

II. List of Reprints

The reprints are organized by work unit as in the Annual Report on this contract. Numbers in parenthesis indicate reference to fiche number and page. The page numbers are coded to the work unit numbers. Note that fiche #7 contains this printed index.

2.1 TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE

WU#1 Multidimensional Digital Signal Processing
R. W. Schafer

A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "An Iterative Method for Restoring Noisy Blurred Images," Circuits, Systems, and Signal Processing, vol. 3, no. 2, June 1984. (Fiche #1, pp. 1-1 to 1-22)

P. A. Maragos, R. W. Schafer, and R. M. Mersereau, "Two-Dimensional Linear Prediction and Its Application to Adaptive Predictive Coding of Images," IEEE Transactions on Acoustics, Speech and Signal Processing, vol. ASSP-32, pp. 1213-1229, December 1984. (Fiche #1, pp. 1-23 to 1-39)

D. M. Thomas and M. H. Hayes, "Procedures for Signal Reconstruction from Noisy Phase," Proc. 1984 Int. Conf. on Acoust., Speech and Signal Processing, pp. 31.1.1-31.1.4, March 1984. (Fiche #1, pp. 1-40 to 1-43)

J. E. Gaby and M. H. Hayes, "Artificial Intelligence Applied to Spectrum Estimation," Proc. 1984 Int. Conf. on Acoust., Speech and Signal Processing, pp. 13.5.1-13.5.4, March 1984. (Fiche #1, pp. 1-44 to 1-47)

P. A. Maragos, R. M. Mersereau, and R. W. Schafer, "Multichannel Linear Predictive Coding of Color Imaging," Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 29.5.1-29.5.4, March 1984. (Fiche #1, pp. 1-48 to 1-51)

J. E. Bevington and R. M. Mersereau, "A Maximum Likelihood Approach to Image Segmentation by Texture,' Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 32.7.1-32.7.4, March 1984. (Fiche #1, pp. 1-52 to 1-55)

P. A. Maragos and R. W. Schafer, "Morphological Skeleton Representation and Coding of Binary Images," Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 29.2.1-29.2.4, March 1984. (Fiche #1, pp. 1-56 to 1-59)

A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "An Iterative Method for Restoring Noisy Blurred Images," Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 37.2.1-37.2.4, March 1984. (Fiche #1, pp. 1-60 to 1-63)

R. M. Mersereau, "Iterative Algorithms for Deconvolution and Reconstruction of Multidimensional Signals From Their Projections," Nato Advanced Study Institute on Adaptive Methods in Underwater Acoustics. (Fiche #1, pp. 1-64 to 1-79)

M. H. Hayes, "Signal Reconstruction From Spectral Phase or Spectral Magnitude," Advances in Computer Vision and Image Processing, vol. 1, pages 145-189, 1984. (Fiche #2, pp. 2-1 to 2-45)

WU#2 **Multiprocessor Architectures for Digital Signal Processing**
T. P. Barnwell, III

D. A. Schwartz and T. P. Barnwell III, "A Graph Theoretic Technique for the Generation of Systolic Implementations for Shift-Invariant Flow Graphs," Proc. of the International Conference on Acoustics, Speech and Signal Processing, March 1984. (Fiche #2, pp. 2-46 to 2-49)

D. A. Schwartz and T. P. Barnwell III, "Increasing the Parallelism of Filters Through Transformation to Block State Variable Form," Proc. of the International Conference on Acoustics, Speech and Signal Processing, March 1984. (Fiche #2, pp. 2-50 to 2-53)

M.J.T. Smith and T.P. Barnwell, III, "A Procedure for Designing Exact Reconstruction Filter Banks for Tree-Structured Subband Coders," Proc. ICASSP'84, March 1984. (Fiche #2, pp. 2-54 to 2-57)

WU#3 **Two-Dimensional Optical Storage & Processing**
T. K. Gaylord

T. K. Gaylord, and C. C. Guest, "Optical Interferometric Liquid Gate Plate Positioner," Review of Scientific Instruments, vol. 55, pp. 866-868, June 1984. (Fiche #2, pp. 2-58 to 2-60)

C. C. Guest, M. M. Mirsalehi, and T. K. Gaylord, "Residue Number System Truth-Table Look-Up Processing: Moduli Selection and Logical Minimization," IEEE Transactions on Computers, vol. C-33, pp. 927-931, October 1984. (Fiche #2, pp. 2-61 to 2-65)

M. G. Moharam, T. K. Gaylord, G. T. Sincerbox, H. Werlich, and B. Yung, "Diffraction Characteristics of Photoresist Surface-Relief Gratings," Applied Optics, vol. 23, pp. 3214-3220, September 15, 1984. (Fiche #2, pp. 2-66 to 2-72)

C. C. Guest, M. M. Mirsalehi, and T. K. Gaylord, "EXCLUSIVE OR Processing (binary image subtraction) using Thick Fourier Holograms," Applied Optics, vol. 23, pp. 3444-3454, October 1, 1984. (Fiche #2, pp. 2-73 to 2-83)

T. K. Gaylord, and M. G. Moharam, "Analysis and Applications of Optical Diffraction by Gratings," Proceedings of the IEEE, vol. 73, pp. xxx-xxx, 1985. (invited paper preprint). (Fiche #3, pp. 3-1 to 3-98 and Fiche #4, pp. 4-1 to 4-85)

T. K. Gaylord, M. M. Mirsalehi, and C. C. Guest, "Optical Digital Truth-Table Look-Up Processing," Optical Engineering, vol. 24, pp. xx-xx, January/February, 1985. (invited paper preprint). (Fiche #5, pp. 5-1 to 5-48)

WU#4 **Two-Dimensional Optical/Electronic Signal Processing**
W. T. Rhodes

William T. Rhodes and Peter S. Guilfoyle, "Acousto-Optic Algebraic Processing Architectures," Proceedings of the IEEE, Vol. 72, No. 7, July 1984 (special issue on Optical Computing), pp. 820-830 (invited). (Fiche #5, pp. 5-49 to 5-59)

H. John Caulfield and William T. Rhodes, "Optical Algebraic Processing Architectures and Algorithms," in Optical Computing, John A. Neff, ed. (SPIE, Vol. 456, Jan. 1984) (invited). (Fiche #5, pp. 5-60 to 5-72)

2.2 **THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS**

WU#5 **Electromagnetic Measurements in the Time- and Frequency-Domains**
G. S. Smith

G. S. Smith, "Limitations on the Size of Miniature Electric Field Probes," IEEE Trans. Microwave Theory and Tech., vol. MIT-32, pp. 594-600, June 1984. (Fiche #5, pp. 5-73 to 5-79)

G. S. Smith, "Limitations on the Size of Miniature Electric Field Probes-The Smallest Dipoles," 1984 IEEE Antenna and Propagation Society, International Symposium and National Radio Science Meeting (URSI), Boston, MA, June 1984. (Fiche #5, pp. 5-80 to 5-83)

G. S. Smith and L. C. Shen, "The Circular Loop Antennas in the Presence of a Material Body," (invited paper) XXIst General Assembly of the International Union of Radio Science (URSI), Florence, Italy, August-September 1984. (Fiche #5, pp. 5-84)

WU#6 **Automated Radiation Measurements for Near- and Far-Field Transformations**
E. B. Joy

E.B. Joy and J.B. Rowland, Jr., "Spherical Surface Sampling," Proceedings of the U.R.S.I. National Radio Science Meeting," Boston, MA, June 25-28, 1984. (Fiche #6, pp. 6-1 to 6-38)

E.B. Joy and D.E. Ball, "A Fast Ray Tracing Algorithm for Arbitrary Monotonically - Concave Three-Dimensional Radome Shapes," Proceedings of the Seventeenth Symposium on Electromagnetic Windows, p. 59, Atlanta, GA, July 25-27, 1984. (Fiche #6, pp. 6-39 to 6-64)

E.B. Joy and H.L. Rappaport, "PWS Radome Analysis Including Reflections," Proceedings of the Seventeenth Symposium on Electromagnetic Windows, p. 57, Atlanta, GA, July 25-27, 1984. (Fiche #6, pp. 6-65 to 6-98)

M.B. Punnett and E.B. Joy, "A Computer Analysis of the RF Performance of a Ground-Mounted Air-Supported Radome," Proceedings of the Seventeenth Symposium on Electromagnetic Windows, pp. 9-16, Atlanta, GA, July 25-27, 1984. (Fiche #7, pp. 7-1 to 7-8)

E.B. Joy, "A Near-Field Radar Cross-Section Measurement Technique," Proceedings of the Annual Conference of the Antenna Measurement Techniques Association, p. 2B6-1, San Diego, CA, October 2-4, 1984. (Fiche #7, pp. 7-9 to 7-28)

L.E. Corey and E.B. Joy, "Hexagonal Sampling in Near Field Measurements," Proceedings of the Annual Conference of the Antenna Measurement Techniques Association, pp. 3A4-1-3A4-16, San Diego, CA, October 2-4, 1984. (Fiche #7, pp. 7-29 to 7-41)

J.A. Donovan and E.B. Joy, "A Cylindrical Near Field Test Facility for UHF Television Transmitting Antennas," Proceedings of the Annual Conference of the Antenna Measurement Techniques Association, p. 4A3-1, San Diego, CA, October 2-4, 1984. (Fiche #7, pp. 7-42)

ANNUAL REPORT APPENDIX
REPRINTS
Joint Services Electronics Program
DAAG29 - 84 - K - 0024
January 1, 1985 - December 31, 1985

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

JANUARY 1986

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

ANNUAL REPORT APPENDIX

Joint Services Electronics Program

DAAG29-84-K-0024

January 1, 1985 - December 31, 1985

Publications

On

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

January, 1986
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LD	GROUP	SUB. GR.	Signal processing, holographic storage, digital filtering, iterative signal restoration, multiprocessors optical computing, electromagnetic measurements.

STRACT (Continue on reverse if necessary and identify by block number)

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2.1 TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE

Work Unit Number 1 - Multidimensional Digital Signal Processing

1.8. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "A general formulation of constrained iterative restoration algorithms", *Proc. 1985 IEEE Int. Conf. Acoustics, Speech, Signal Processing*, pp. 700-703. (Fiche pp. 1-536 through 1-539.)

1.9. P. A. Maragos and R. W. Schafer, "A unification of linear, median, order-statistics, and morphological filters under mathematical morphology," *Proc. 1985 IEEE Int. Conf. Acoustics, Speech Signal Processing*, pp. 1329-1332. (Fiche pp. 1-540 through 1-543.)

Work Unit Number 2 - Multiprocessor Architectures for Digital Signal Processing

2.1. D. A. Schwartz, "Synchronous Multiprocessor Realization of Shift-Invariant Flow Graphs," Ph.D. Thesis, Georgia Institute of Technology, June 1985. (Fiche pp. 2-1 through 2-198.)

2.2 D. A. Schwartz and T. P. Barnwell III, "Cyclo-static Multiprocessor Scheduling for the Optimal Realization of Shift-Invariant Flow Graphs," *Proc. 1985 Int. Conf. Acoustics, Speech and Signal Processing*, pp. 1384-1387, March 1985. (Fiche pp. 2-199 through 2-202.)

2.3. S. H. Lee, C. J. M. Hodges, and T. P. Barnwell III, "An SSIMD Compiler for the Implementation of Linear Shift-Invariant Flow Graphs," *Proc. 1985 Int. Conf. Acoustics, Speech and Signal Processing*, pp. 1664-1667, March 1985. (Fiche pp. 2-203 through 2-206.)

2.4. M.J.T. Smith and T.P. Barnwell, III, "A Unifying Framework for Analysis/Synthesis Systems Based on Maximally Decimated Filter Banks," *Proc. 1985 Int. Conf. Acoustics, Speech and Signal Processing*, pp. 521-524, March, 1985. (Fiche pp. 2-207 through 2-210.)

Work Unit Number 3 - Two-Dimensional Optical Storage and Processing

3.1. M. M. Mirsalehi, "Two-Dimensional Optical Storage and Processing," Ph.D. Thesis, Georgia Institute of Technology, August, 1985. (Fiche pp. 3-1 through 3-192.)

3.2. C. C. Guest and T. K. Gaylord, "Phase stabilization system for real-time image subtraction and logical EXCLUSIVE OR processing," *Applied Optics*, vol. 24, pp. 2140-2144, July 15, 1985. (Fiche pp. 3-193 through 3-197.)

3.3. R. S. Weis and T. K. Gaylord, "Lithium niobate: Summary of physical properties and crystal structure," *Applied Physics A*, vol. 37, pp. 191-203, August 1985. (invited) (Fiche pp. 3-198 through 3-210.)

3.4. A. Knoesen, M. G. Moharam, and T. K. Gaylord, "Surface impedance/admittance approach for solving isotropic and anisotropic propagation problems," *Applied Physics B*, vol. 38, pp. 171-178, November 1985. (Fiche pp. 3-211 through 3-218.)

3.5. T. K. Gaylord and M. G. Moharam, "Analysis and applications of optical diffraction by gratings," *Proceedings of the IEEE*, vol. 73, pp. 894-937, May 1985. (invited) (Fiche pp. 3-219 through 3-210.)

3.6. T. K. Gaylord, M. M. Mirsalehi, and C. C. Guest, "Optical digital truth-table look-up processing," *Optical Engineering*, vol. 24, pp. 45-58, January/February 1985. (invited) (Fiche pp. 3-263 through 3-273.)

3.7. T. K. Gaylord and M. M. Mirsalehi, "Truth-table look-up processing: Number representation, multilevel coding, and logical minimization," *Optical Engineering*, vol. 25, pp. 22-28, January/February 1986. (invited) (Fiche pp. 3-274 through 3-280.)

Work Unit Number 4 - Two-Dimensional Optical/Electronic Signal Processing

4.1. Joseph N. Mait, "Pupil Function Optimization for Bipolar Incoherent Spatial Filtering," Ph.D. Thesis, Georgia Institute of Technology, June, 1985. (Fiche pp. 4-1 through 4-205.)

Work Unit Number 5 - Optimal Multiprocessor Structures for the Implementation of DSP Algorithms on High-Density Integrated Circuits

Since this work unit has only existed since April 15, 1985, there were no publications in 1985.

2.2 THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

Work Unit Number 6 - Electromagnetic Measurements in the Time- and Frequency-Domains

6.1. W. R. Scott, Jr., "Dielectric Spectroscopy Using Shielded Open-Circuit Coaxial Lines and Monopole Antennas of General Length," *Ph.D. Thesis, School of Electrical Engineering, Georgia Institute of Technology*, Atlanta, Georgia, October 1985. (Fiche pp. 6-1 through 6-251.)

6.2. G. S. Smith and J. D. Nordgard, "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas," *IEEE Trans. Antennas and Propagat.*, Vol. AP-33, pp. 783-792, July 1985. (Fiche pp. 6-252 through 6-261.)

6.3. G. S. Smith, "Measurement of the Permittivity of Materials Using Monopole Antennas," *1985-IEEE Antennas and Propagation Society, International Symposium*, Vancouver, Canada, pp. 517-520, June 1985. (Fiche pp. 6-262 through 6-265.)

6.4. W. R. Scott, Jr. and G. S. Smith, "Dielectric Spectroscopy Using Open-Circuited Coaxial Lines of General Length," *1985 North American Radio Science Meeting*, Vancouver, Canada, pg. 36, June 1985. (Fiche pg. 6-266.)

Work Unit Number 7 - Automated Radiation Measurements for Near- and Far-Field Transformations

7.1. E. B. Joy and J. B. Rowland, Jr., "Sample Spacing and Position Accuracy Requirements for Spherical Surface Near-Field Measurements," *Proceedings of the 1985 IEEE/AP-S International Symposium*, Vancouver, B.C., June 17-21, 1985, pp. 682-692. (Fiche pg. 7-1.)

7.2. E. B. Joy, Near-Field Radar Crossection Measurement," *Proceedings of the Antenna Measurement Techniques Association Workshop on RCS Measurement Techniques*, Vancouver, B.C., June 21, 1985. (Fiche pp. 7-2 through 7-10.)

7.3. E. B. Joy and J. B. Rowland, Jr., "Sample Spacing Requirements for Spherical Surface Near-Field Measurements," *Proceedings of the 1985 Antenna Measurement Techniques Association Meeting*, Melbourne, FL, October 29-31, 1985, pp. 2-1, 2-10. (Fiche pp. 7-11 through 7-24.)

7.4. K. W. Cozad and E. B. Joy, "An Outdoor UHF Cylindrical Surface Near-Field Range," *Proceedings of the 1985 Antenna Measurement Techniques Association Meetings*, Melbourne, FL, October 29-31, 1985, pp. 4-1, 4-8. (Fiche pp. 7-25 through 7-32.)

7.5. E. B. Joy, O. D. Asbell and R. C. Johnson, "Feasibility of a Large Outdoor Compact Range," *Proceedings of the 1985 Antenna Measurement Techniques Association Meeting*, Melbourne, FL, October 29-31, 1985, pp. 11-1, 11-6. (Fiche pp. 7-33 through 7-38.)

7.6. E. B. Joy, B. K. Rainer and B. L. Shirley, "Monostatic Near-Field Radar Cross-Section Measurement," *Proceedings of the 1985 Antenna Measurement Techniques Association Meeting*, Melbourne, FL, October 29-31, 1985, pp. 24-1, 24-11. (Fiche pp. 7-39 through 7-49.)

ANNUAL REPORT APPENDIX
REPRINTS
Joint Services Electronics Program
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TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

JANUARY 1987

GEORGIA INSTITUTE OF TECHNOLOGY
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ANNUAL REPORT APPENDIX

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Publications
on

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE
AND
THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

January, 1987
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

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2.1 TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE

Work Unit Number 1 - Multidimensional Digital Signal Processing

1.7 Wilkes, D. M., and Hayes, M. H., "Spectral line tracking for nonstationary random processes", *Proc. 1986 Int. Conf. on Acoustics, Speech, and Sig. Proc.*, pp. 2347-2350, April 1986. (pages 1-104 to 1-107 on microfiche)

1.8 Karlsson, E., and Hayes, M. H., "ARMA modeling of time-varying systems with lattice filters", *Proc. 1986 Int. Conf. on Acoustics, Speech, and Sig. Proc.*, pp. 2335-2338, April 1986. (pages 1-108 to 1-111 on microfiche)

1.9 Hayes, M. H., Wilkes, D. M., and Mazel, D., "Iterative harmonic decomposition of nonstationary random processes and its application to spectral line tracking and speech encoding", *Proc. 1986 IEEE - Academia Sinica Workshop on Acoust., Speech, and Sig. Proc.*, pp. 55-58, Beijing, China, April 1986. (pages 1-112 to 1-115 on microfiche)

1.10 Morris, C. E., Richards, M. A., and Hayes, M. H., "An iterative deconvolution algorithm with exponential convergence", *Proc. Opt. Soc. Am. Topical Conf. on Signal Recovery*, pp. 112-115, Hawaii, April 1986. (pages 1-116 to 1-119 on microfiche)

1.11 Wilkes, D. M., and Hayes, M. H., "Symmetric Toeplitz matrices: A recursion for the eigenvalues", *Proc. 1986 Dig. Sig. Proc. Workshop*, pp. 7.7.1-7.7.2, October, 1986. (pages 1-120 to 1-121 on mirofiche)

1.12 Morris, C. E., Richards, M. A., and Hayes, M. H., "An iterative deconvolution algorithm with p^{th}-order convergence", *Proc. 1986 Dig. Sig. Proc. Workshop*, pp. 4.8.1-4.8.2, October, 1986. (pages 1-122 to 1-123 on microfiche)

1.13 Maragos, P. A., and Schafer, R. W., "Applications of Morphological Filtering to Image Analysis and Processing," *Proc. 1986 Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. 39.6.1-39.6.4. (pages 1-124 to 1-127 on microfiche)

1.14 AuYeung, C., Mersereau, R. M., and Schafer, R. W., "Maximum entropy deconvolution," *Proceedings 1986 IEEE International Conference on Acoustics, Speech and Signal Processing*, pp. 273-276. (pages 1-128 to 1-131 on microfiche)

1.15 Bevington, J. E., and Mersereau, R. M., "A random field model-based algorithm for textured image segmentation," *EUSIPCO-86, Third European Signal Processing Conference Signal Processing III: Theories and Applications* (Young et al. editors), pp. 909-912, 1986. (pages 1-132 to 1-135 on microfiche)

Work Unit Number 2 - Multiprocessor Architectures for Digital Signal Processing

2.1 Sae Hun Lee, "A Unified Approach to Optimal Multiprocessor Implementations from Non-parallel Algorithm Specifications," Ph.D. Thesis, Georgia Institute of Technology, October, 1986. (pages 2-1 to 2-277 on microfiche)

2.2 M. J. T. Smith and T. P. Barnwell, III, "Exact Reconstruction Techniques for Tree-Structured Subband Coders," *IEEE Transactions on ASSP*, June, 1986. (pages 2-278 to 2-311 on microfiche)

2.3 D. A. Schwartz, T. P. Barnwell, III and C. J. M. Hodges, "The Optimal Synchronous Cyclo-Static Array: A Multiprocessor Supercomputer for Digital Signal Processing," *1986 International Conference on Acoustics, Speech, and Signal Processing*, Tokyo, Japan, April, 1986. (pages 2-312 to 2-315 on microfiche)

2.4 S. H. Lee and T. P. Barnwell, III, "A Topological Sorting and Loop Cleansing Algorithm for a Constrained MIMD Compiler of Shift-Invariant Flow Graphs," *1986 International Conference on Acoustics, Speech, and Signal Processing*, Tokyo, Japan, April, 1986. (pages 2-316 to 2-319 on microfiche)

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3.1 Mirsalehi, M. M. and Gaylord, T. K., "Comments on direct implementation of discrete and residue-based functions via optimal encoding: A programmable array logic approach," *IEEE Transactions on Computers*, vol. C-35, pp. 829-830, September 1986. (pages 3-1 to 3-2 on microfiche)

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3.7 Gaylord, T. K., Baird, W. E., and Moharam, M. G., "Zero-reflectivity high spatial-frequency rectangular-groove dielectric surface-relief gratings," *Applied Optics*, vol. 25, pp. 4562-4567, December 15, 1986. (pages 3-43 to 3-48 on microfiche)

Work Unit Number 4 - Two-Dimensional Optical/Electronic Signal Processing

4.1 Mait, Joseph N. and Rhodes, William T., "Two-pupil synthesis of optical transfer functions: 2-pupil function relationships," *Applied Optics*, Vol. 25 (15 June 1986), pp. 2003-2007. (pages 4-1 to 4-5 on microfiche)

4.2 Mait, Joseph N., "Existence conditions for two-pupil synthesis of bipolar incoherent point-spread functions," *Journal of the Optical Society of America A*, Vol. 3 (April 1986), pp. 437-445. (pages 4-6 to 4-14 on microfiche)

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4.6 O'Neill, Kirt S. and Rhodes, William T., "Morphological Transformations by Hybrid Optical-Electronic Methods," in *Hybrid Image Processing*, D. Casasent and A. Tescher, eds. (Proc. SPIE, vol. 638, 1986), pp. 41-44. (pages 4-26 to 4-29 on microfiche)

4.7 Rhodes, William T., Stroud, Robert, and Gaynor, Edwin S., "Maximizing Diffraction Efficiency of Bleached Time-Integration-Exposure Silver-Halide Holograms," in *Holography Technical Digest* (Optical Society of America, 1986), pp. 96-99. (pages 4-30 to 4-33 on microfiche)

Work Unit Number 5 - Optimal Multiprocessor Structures for the Implementation of DSP Algorithms on High-Density Integrated Circuits

5.1 Schwartz, D. A. and Barnwell, T. P., III, and Hodges, C. J. M., "The Optimal Synchronous Cyclo-Static Array: A Multiprocessor Supercomputer for Digital Signal Processing," *Proc. of the International Conference on Acoustics, Speech and Signal Processing*, Tokyo, Japan, April 1986. (pages 5-2 to 5-4 on microfiche)

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2.2 THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

Work Unit Number 6 - Electromagnetic Measurements in the Time- and Frequency-Domains

6.1 Scott, W. R., Jr., and Smith, G. S., "Error analysis for Dielectric Spectroscopy Using Shielded Open-Circuited Coaxial Lines of General Length," *IEEE Trans. Instrumentation and Measurements*, Vol. IM-35, pp. 130-137, June 1986. (pages 6-1 to 6-8 on microfiche)

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6.3 Scott, W. R., Jr., and Smith, G. S., "Error Corrections for an Automated Time-Domain Network Analyzer," *IEEE Trans. Instrumentation and Measurements*, Vol. IM-35, pp. 300-303, September 1986. (pages 6-20 to 6-23 on microfiche)

6.4 Scott, W. R., Jr., and Smith, G. S., "Dielectric Spectroscopy Using Monopole Antennas of General Electrical Length," 1986 International IEEE Antennas and Propagation Symposium, Philadelphia, PA, June 1986. (pages 6-24 to 6-27 on microfiche)

Work Unit Number 7 - Automated Radiation Measurements for Near- and Far-Field Transformations

7.1 Effenberger, J. A., Strickland, R. R., and Joy, E. B., "The Effects of Rain on a Radome's Performance," *Microwave Journal*, Vol. 29, No. 5, May 1986, pp. 261-274. (pages 7-1 to 7-7 on microfiche)

7.2 Joy, E. B., Wilson, R. E., Caraway, W. D., Hill, C., and Edwards, S. J., "Near Field Measurement of Radome Performance," *Proceedings of the Eighteenth Symposium on Electromagnetic Windows*, Atlanta, Georgia, September 17-19, 1986. (pages 7-8 to 7-13 on microfiche)

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7.4 Joy, E. B., and Wilson, R. E., "Spectral Evaluation of Reflector Surfaces Used for Compact Ranges," *Proceedings of the 1986 Antenna Measurement Techniques Association Workshop*, Philadelphia, PA, June 13, 1986. (pages 7-35 to 7-48 on microfiche)

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FINAL REPORT
Joint Services Electronics Program
DAAG29 - 84 - K - 0024
April 1, 1984 - March 31, 1987

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

OCTOBER 1987

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

TECH

Two-Dimensional Signal Processing and Storage and Theory and Applications of Electromagnetic Measurements

Joint Services Electronics Program
Contract DAAG29-84-K-0024
April 1, 1984 to March 31, 1987
Final Report

Contents

1 Introduction

This final report on basic research in signal processing and electromagnetic measurements lists the work units and principal investigators, graduate degrees awarded, and publications during the three year contract period. The report concludes with brief discussions of the major results and contributions of the research.

2 Work Units

2.1 Two-Dimensional Signal Processing and Storage

Work Unit One: *Multidimensional Digital Signal Processing*
Principal Investigator: Ronald W. Schafer, Regents' Professor, R. M. Mersereau, Regents' Professor, and M. H. Hayes, Associate Professor

Work Unit Two: *Multiprocessor Architectures for Digital Signal Processing*
Principal Investigator: Thomas P. Barnwell III, Professor

Work Unit Three: *Two-Dimensional Optical Storage and Processing*
Principal Investigator: Thomas K. Gaylord, Regents' Professor

Work Unit Four: *Two Dimensional Optical/Electronic Signal Processing*
Principal Investigator: W. T. Rhodes, Professor

Work Unit Five: *Optimal Multiprocessor Structures for the Implementation of Digital Signal Processing Algorithms on High Density Integrated Circuits*
Principal Investigators: D. A. Schwartz, Assistant Professor and J. H. Schlag, Professor

2.2 Theory and Application of Electromagnetic Measurements

Work Unit Six: *Electromagnetic Measurements in the Time- and Frequency-Domains*
Principal Investigator: G. S. Smith, Professor

Work Unit Seven: *Automated Radiation Measurements for Near- and Far-Field Transformations*
Principal Investigator: E. B. Joy, Professor

3 Degrees Awarded

A. Guessoum - Ph.D., September 1984
Thesis: Fast algorithms for the multidimensional discrete Fourier transform

C. J. M. Hodges - MS, May 1985
Thesis: Skewed Single Instruction Multiple Data Computation

A. K. Katsaggelos - Ph.D., September 1985
Thesis: Constrained iterative image restoration algorithms

S. H. Lee - Ph.D., December 1986
Thesis: A unified approach to optimal multiprocessor implementations from non-parallel algorithm specifications

J. N. Mait - Ph.D., June 1985
Thesis: Pupil function optimization for bipolar incoherent spatial filtering

P. A. Maragos - Ph.D., September 1985
Thesis: A unified theory of translation-invariant systems with applications to morphological analysis and coding of images

M. M. Mirsalehi - Ph.D., August 1985
Thesis: Two-dimensional optical storage and processing

D. A. Schwartz - Ph.D., September 1985
Thesis: Synchronous multiprocessor realizations of shift-invariant flow graphs

W. R. Scott, Jr. - Ph.D., January 1986
Thesis: Dielectric spectroscopy using shielded open-circuited coaxial lines and monopole antennas of general length

M. J. T. Smith - Ph.D., December 1984
Thesis: Exact reconstruction analysis/synthesis systems and their application to frequency domain coding

4 Publications

4.1 Work Unit One: Multidimensional Digital Signal Processing

Theses:

1. A. Guessoum, "Fast algorithms for the multidimensional discrete Fourier transform," Ph.D. Thesis, Georgia Institute of Technology, June 1984.

2. P. A. Maragos, "A unified theory of translation-invariant systems with applications to morphological analysis and coding of images," Ph.D. Thesis, Georgia Institute of Technology, July 1985.

3. A. K. Katsaggelos, "Constrained iterative image restoration algorithms," Ph.D. Thesis, Georgia Institute of Technology, August 1985.

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1. D. E. Dudgeon and R. M. Mersereau, *Multidimensional Digital Signal Processing*, Prentice-Hall, Englewood Cliffs, NJ, 1984.

2. M. H. Hayes, "Signal Reconstruction from Spectral Phase or Spectral Magnitude," *Advances in Computer Vision and Image Processing*, vol. 1, (T. S. Huang, Ed.) JAI Press, 1984.

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1. A. K. Katsaggelos, J. Biemond, R. M. Mersereau and R. W. Schafer, "An iterative method for restoring noisy blurred images," *Circuits, Systems and Signal Processing*, vol. 3, no. 2, June 1984.

2. P. A. Maragos, R. W. Schafer and R. M. Mersereau, "Two-dimensional linear prediction and its application to adaptive predictive coding of images," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, December 1984.

3. M. H. Hayes and M. A. Clements, "An efficient algorithm for computing Pisarenko's harmonic decomposition using Levinson's recursion," *IEEE Trans. on Acoust., Speech, Sig. Proc.*, vol. ASSP-34, no. 3, pp. 485-491, June 1986.

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21. E. Karlsson and M. H. Hayes, "Modeling of time-varying systems with ARMA lattice filters," *Proc. 1986 Int. Conf. on Acoustics, Speech, and Sig. Proc.*, pp. 2335-2338, April 1986.

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4.2 Work Unit Two: Multidimensional Digital Signal Processing

Theses:

1. M. J. T. Smith, "Exact reconstruction analysis/synthesis systems and their application to frequency domain coding," Ph.D. Thesis, Georgia Institute of Technology, December 1984.

2. C. J. M. Hodges, "Skewed single instruction multiple data computation," Master's Thesis, Georgia Institute of Technology, May 1985.

3. D. A. Schwartz, "Synchronous multiprocessor realization of shift-invariant flow graphs," Ph.D. Thesis, Georgia Institute of Technology, June 1985.

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1. D. A. Schwartz and T. P. Barnwell, III, "A graph theoretic technique for the generation of systolic implementations for shift-invariant flow graphs," *Proc. of the International Conference on Acoustics, Speech and Signal Processing*, March 1984.

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7. D. A. Schwartz, T. P. Barnwell, III and C. J. M. Hodges, "The optimal synchronous cyclo-static array: A multiprocessor supercomputer for digital signal processing," *1986 International Conference on Acoustics, Speech, and Signal Processing*, Tokyo, Japan, April, 1986.

8. S. H. Lee and T. P. Barnwell, III, "A topological sorting and loop cleansing algorithm for a constrained MIMD compiler of shift-invariant flow graphs," *1986 International Conference on Acoustics, Speech, and Signal Processing*, Tokyo, Japan, April, 1986.

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4.3 Work Unit Three: Two-Dimensional Optical Storage and Processing

Theses:

1. M. M. Mirsalehi, "Two-dimensional optical storage processing," Ph.D. Thesis, Georgia Institute of Technology, August 1985.

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1. T. K. Gaylord and C. C. Guest, "Optical interferometric liquid gate plate positioner," *Review of Scientific Instruments*, vol. 55, pp. 866-868, June 1984.

2. C. C. Guest, M. M. Mirsalehi, and T. K. Gaylord, "Residue number system truth-table loop-up processing: moduli selection and logical minimization," *IEEE Transactions on Computers*, vol. C-33, pp. 927-931, October 1984.

3. M. G. Moharam, T. K. Gaylord, G. T. Sincerbox, H. Werlich, and B. Yung, "Diffraction characteristics of photoresist surface-relief gratings," *Applied Optics*, vol. 23, pp. 3214-3220, September 15, 1984.

4. C. C. Guest, M. M. Mirsalehi, and T. K. Gaylord, "EXCLUSIVE OR processing (binary image subtraction) using thick Fourier holograms," *Applied Optics*, vol. 23, pp. 3444-3454, October 1, 1984.

5. C. C. Guest and T. K. Gaylord, "Phase stabilization system for real-time image subtraction and logical EXCLUSIVE OR processing," *Applied Optics*, vol. 24, pp. 2140-2144, July 15, 1985.

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7. A. Knoésen, M. G. Moharam and T. K. Gaylord, "Surface impedance/admittance approach for solving isotropic and anisotropic propagation problems," *Applied Physics B*, vol. 38, pp. 171-178, November 1985.

8. T. K. Gaylord and M. G. Moharam, "Analysis and applications of optical diffraction by gratings," *Proceedings of the IEEE*, vol. 73, pp. 894-937, May 1985. (invited)

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11. M. M. Mirsalehi and T. K. Gaylord, "Multi-level coded residue-based content-addressable-memory optical computing," *Applied Optics*, vol. 25, pp. 2277-2283, July 15, 1986.

12. T. K. Gaylord and M. M. Mirsalehi, "Truth-table look-up processing: number representation, multi-level coding, and logical minimization," *Optical Engineering*, vol. 25, pp. 22-28, January 1986. (invited).

13. M. M. Mirsalehi, T. K. Gaylord, and E. I. Verriest, "Integrated optical Givens rotation device," *Applied Optics*, vol. 25, pp. 1608-1614, May 15, 1986.

14. M. M. Mirsalehi and T. K. Gaylord, "Logical minimization of multilevel coded functions, *Applied Optics*, vol. 25, pp. 3078-3088, September 15, 1986. (invited).

15. M. G. Moharam and T. K. Gaylord, "Rigorous coupled-wave analysis of metallic surface-relief gratings," *Journal of the Optical Society of America A*, vol. 3, pp. 1780-1787, November 1986.

16. T. K. Gaylord, W. E. Baird and M. G. Moharam, "Zero-reflectivity high spatial-frequency rectangular-groove dielectric surface-relief gratings," *Applied Optics*, vol. 25, pp. 4562-4567, December 15, 1986.

4.4 Work Unit Four: Two-Dimensional Optical/Electronic Signal Processing

Theses:

1. Joseph N. Mait, "Pupil function optimization for bipolar incoherent spatial filtering," Ph.D. Thesis, Georgia Institute of Technology, June 1985.

Other Publications:

1. William T. Rhodes and Peter S. Guilfoyle, "Acousto-optic algebraic processing architectures," *Proceedings of the IEEE*, Vol. 72, No. 7, July 1984 (special issue on Optical Computing), pp. 820-830. (Invited)

2. H. John Caulfield and William T. Rhodes, "Optical algebraic processing architectures and algorithms," in *Optical Computing*, John A. Neff, ed. (SPIE, Vol. 456, January 1984). (Invited)

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4. E. S. Gaynor and W. T. Rhodes, "Exposure optimization for incoherent computer holography," presented at *1985 Annual Meeting of the Optical Society of America*, Washington, DC, October 1985.

5. Joseph N. Mait and W. T. Rhodes, "Two-pupil synthesis of optical transfer functions: 2-pupil function relationships," *Applied Optics*, Vol. 25, pp. 2003-2007, June 15, 1986.

6. Joseph N. Mait, "Existence conditions for two-pupil synthesis of bipolar incoherent point-spread functions," *Journal of the Optical Society of America A*, Vol. 3, pp.437-445, April 1986.

7. Joseph N. Mait, "Pupil-function design for bipolar incoherent spatial filtering," *Journal of the Optical Society of America A*, Vol. 3, pp. 1826-1832, April 1986.

8. Joseph N. Mait, "Existence and synthesis of bipolar incoherent pointspread functions," in *Signal Recovery & Synthesis II*, Technical Digest of Optical Optical Society of America Topical Meeting, Honolulu, pp. 27-30, April 1986.

9. Kirt S. O'Neill, and William T. Rhodes, "Morphological transformations by hybrid optical-electronic methods," in *Hybrid Image Processing*, D. Casasent and A. Tescher, eds. (Proc. SPIE, vol. 638), pp. 41-44, 1986.

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4.6 Work Unit Six: Electromagnetic Measurements in the Time and Frequency Domains

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2. G. S. Smith and J. D. Nordgard, "Measurement of the electrical constitutive parameters of materials using antennas," *IEEE Trans. Antennas and Propagation*, Vol. AP-33, ,pp. 783-792, July 1985.

3. G. S. Smith, "Measurement of the permittivity of material using monopole antennas," *1985-IEEE Antennas and Propagation Society, International Symposium*, Vancouver, Canada, pp. 517-520, June 1985.

4. W. R. Scott, Jr. and G. S. Smith, "Error analysis for dielectric spectroscopy using shielded open-circuited coaxial lines of general length," *IEEE Trans. Instrumentation and Measurements*, Vol. IM-35, pp. 130-137, June 1986.

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2. E. B. Joy, A. L. Maffett and J. Frank, *Radar Cross-Section Measurement Techniques*, Technology Service Corporation, 1984.

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2. E. B. Joy and J. B. Rowland, Jr., "Spherical surface sampling," *Proceedings of the URSI National Radio Science Meeting*, Boston, MA, June 25-28.

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5 Individual Reports - Summary of Accomplishments

5.1 Work Unit One

Image Segmentation by Texture Automatically segmenting a visual image into its component parts is an important first step in most computer vision tasks, ranging from industrial robotics to automatic target identification. In important special cases involving flat, well-lighted, man-made objects, recorded in a relatively noise-free environment, this task is accomplished straightforwardly using edge detectors followd by some heuristic procedures for completing contours and removing noise spikes. The problem becomes much more difficult when the images are noisy or when textured images are involved. (The concept of texture is rarely defined precisely, but it corresponds to the degree of roughness or smoothness of a surface.) Traditional methods for edge detection do not work in these cases.

Work performed under this work unit has resulted in the development of an optimal detector for edges in textures images, known as the maximum likelihood (ml) textured edge detector. A computer program has been written for segmenting arbitrary textured images which incorporates the ml detector. This program also incorporates some prior knowledge about the shapes and sizes of permissible regions in performing the segmentation.

Mathematical Morphology The theory of mathematical morphology is an approach to the representation of images and image processing systems that seeks to quantitatively represent geometrical structure in images. The key to this approach is that signals are represented by sets rather than by functions, and therefore systems (or image transformations) are represented as set transformations. Sets or collections of image points are a much more natural representation for displaying geometrical structure, particularly for binary images, but the concept can also be extended to gray-level images.

Research at Georgia Tech has resulted in the development of a general theory of translation-invariant morphological systems. This general theory, developed in a thesis by Maragos, significantly extends the theory of mathematical morphology and it unifies a wide range of commonly used image processing operations under a common framework. This research shows that this theory can be applied to morphological filters, median filters, order-statistics filters, edge detectors, shape recognition transformations and an interesting class of linear shift-invariant systems. The theory has already lead to new insights into the properties of such systems and also to new approaches to the implementation of such systems. The theory also may provide a framework in which to develop new approaches to the synthesis of image transformations with prescribed properties. Other research in this area has investigated the use of skeleton representations of geometric structure in images. Skeletons, which are line-thinned caricatures of the shapes in the image which contain complete information for reconstructing the original image, and they display information about size, shape, orientation, and connectivity of the image objects. An important application of this work is in digital coding of binary images, where skeleton coding methods have been shown to more efficient than optimum run-length coding.

Maximum Entropy Image Deblurring Images can be blurred by camera motion, out-of-focus optics, or atmospheric turbulence. Removing the distortions introduced by these blurs is often necessary for either human or automatic photo interpretation. Traditional methods for computer deblurring have been performed by designing special linear filters (inverse filters, Wiener filters, Kalman filters), but the performance of these filters is limited by the measurement noise which is inevitably present. Their performance can be improved by incorporating prior knowledge about the underlying object, e.g. that the object imaged is of finite extent, that the object intensity values are bounded, etc. Recent research here and elsewhere has demonstrated the superior performance of a number of iterative algorithms for blur removal, which are capable of incorporating these types of prior knowledge and which can also be made adaptive. All of this work is based on the minimization of a measure of the squared error.

The work performed under this work unit resulted in the development of procedures for removing blurs from images given a number of constraints on the restored signal. These procedures were not designed to minimize a squared error; rather they were designed to maximize the entropy in the restored image. This will result in a smooth restoration which is different from the least-squares restoration. The maximum entropy restoration is particularly appropriate when the signal consists of a number of point sources superimposed on a non-descript background.

The majority of work in this area has been mathematical although working computer programs for blur removal have been written and a series of experiments involving them are now being performed. These algorithms can determine the maximum entropy restoration subject to upper and lower bounds on the image intensity, an upper bound on the total (integrated) intensity, and constraints on the power and power density spectrum of the measurement noise.

Constrained Convergent Deconvolution Algorithm Iterative algorithms are based on the method of successive approximations and have become very popular for signal deconvolution due to the flexibility that they allow for the incorporation of signal constraints into the restoration. One of the limitations with these iterative algorithms is that they only achieve a linear rate of convergence. However, by viewing the output of each step of the iteration as a modification of the basic distortion equation, it was shown that the observation equation could be similarly updated after each iteration. With this modification, the iteration exhibits a quadratic rate of convergence. As a result, 1024 iterations with the linear algorithm could be realized by using only 10 iterations of the quadratic algorithm. Although there are more arithmetic computations required per iteration using the quadratic algorithm, the total number of arithmetic operations required for a given fidelity in the reconstruction is much less for the quadratic algorithm.

Signal Modeling and Power Spectrum Estimation Power spectrum estimation is a special form of signal reconstruction problem where the autocorrelation function or its Fourier transform must be determined from a finite time observation of a time series or from a noisy and truncated autocorrelation sequence. Power spectrum estimation is, in effect, an extrapolation problem. An approach which is commonly used is to formulate a signal model, estimate the model parameters from the data, and extrapolate the signal or its autocorrelation function from the model. We have considered two problems related to signal modeling and the application of these models to spectrum estimation. The first problem was concerned with the modeling of a signal as the sum of sinusoids in white noise where the sinusoidal frequencies are varying as a function of time. Typically, with such a model an adaptive version of the Pisarenko harmonic decomposition would be applied to the data to extract the model parameters. By exploiting some properties of the Levinson/Durbin recursion, however, a new algorithm was developed. This algorithm is very simple in form and converges quickly to give the desired information. One of the advantages of using this algorithm is that, for non-stationary data, it may be made into an adaptive algorithm where both the white noise power and the minimum eigenvector (eigenfilter) are recursively updated in time.

The second modeling problem considered was concerned with developing an autoregressive moving average lattice filter model for a linear time-varying system. As a result of this work a new ARMA lattice filter structure was developed which is consistent with the characteristics of the well-known autoregressive and moving average lattice filters. In particular, this ARMA lattice is realized in terms of a fully orthogonal lattice set of basis vectors and it evaluates all optimal lattice ARMA filters of lower order. In addition to the ARMA lattice structure, a fast recursive least squares algorithm for the evaluation of the lattice filter coefficients was developed.

5.2 Work Units Two and Five

One of the most important and difficult problems in modern technology is how to apply large numbers of processors in parallel in computationally complex digital signal processing (DSP) applications. The fundamental problem is not the construction of large multiprocessor systems, since modern VLSI techniques can produce very large and inexpensive multiprocessor systems with relative ease. Rather, the fundamental problem is how to design such large machines so they can be programmed to give efficient and effective realizations.

For the past several years, Georgia Tech, under the sponsorship of the JSEP, has been studying techniques for the automatic generation of provably optimal implementations for a large class of DSP algorithms on a large class of synchronous multiprocessors. In this research, both the class of algorithms addressed and the class of multiprocessors targeted are specifically aimed at DSP applications. The algorithms are represented by a class of cyclic shift-invariant flow graphs. DSP algorithms are unique in that they are usually both highly structured and highly computationally intense, and are hence well-matched to a graphical representation. The multiprocessors are synchronous deterministically scheduled MIMD machines. Such multiprocessors are potentially the most cost effective since the precedence relations are all maintained by the synchrony of the system, and no hardware or software is needed to realize semaphore mechanisms.

Georgia Tech has now succeeded in demonstrating three compilers for synchronous multiprocessor systems. These compilers all take advantage of performance bounds which are based on the graph of the algorithm to be implemented and the arithmetic properties of the multiprocessor on which the algorithm is to be realized. These bounds constrain and define the characteristics of the optimal implementations in terms of their speed, delay, and efficiency.

In order to consistently achieve optimal realizations, a new class of multiprocessors, called ***cyclo-static*** processors, has been introduced and developed. Cyclo-static implementations (which include systolic implementations as a static special case) can always be found which achieve the graph bounds, resulting in realizations which are ***rate-optimal*** (optimally fast), ***delay-optimal*** (minimum I/O delay), and ***processor-optimal*** (maximally efficient). The compilers all use the graph bounds to specifically construct only optimal cyclo-static implementations. These has the effect of both reducing the complexity of the compilers while constructing the most desirable class of realizations.

The techniques developed in this research are widely applicable from very low-level systems, such as multiple simple processors on single chips, to very large systems, such as DSP supercomputers. The latter systems require the design of special cyclo-static constituent processors if the full potential of the compilers are to be realized. Two cyclo-static multiprocessors, called Optimal Synchronous Cyclo-Static ARrays or OSCARs, have been designed, and one is currently being constructed.

5.3 Work Unit Three

Integrated Optical Givens Rotation Device The Givens rotation operation occupies a central role in linear algebraic signal processing. An integrated optical coherent implementation of an elementary rotation matrix device, based on thick grating diffraction, to perform this operation has been designed. It has been shown that existing electro-optic and waveguide devices can be combined to produce a fast Givens rotation device. Arrays of these devices can be used to perform matrix triangularization and thus solve large systems of linear equations. Arrays of these devices integrated onto microchips are thus directly applicable in adaptive antenna beam forming, artificial intelligence, remote sensing, ultrahigh resolution image processing, control of communication networks, air traffic control, synthetic aperture radar imaging, missile guidance, defense early warning systems, and simulation problems such as aerodynamic modeling and weather prediction.

Antireflection Grating Surfaces A calculational method for determining the filling factor and the groove depth of a rectangular-groove grating on an arbitrary lossy substrate to produce zero reflectivity has been determined. The method is based on an impedance matching approach. It can be applied to both TE and TM polarization, to any angle of incidence, and to any wavelength. The antireflection behavior has been verified for the gratings using the rigorous (without approximations) coupled-wave analysis of metallic surface-relief grating diffraction. Example zero-reflectivity gold gratings for an incident freespace wavelength in the range from $\lambda_0 = 0.44$ μm to 12.0 μm have been presented. Applications include construction of polarization selective mirrors and windows for high power lasers, higher efficiency photodetectors and solar cells, optical elements such as wave plates and polarizers, and airframes that are antireflecting at microwave frequencies.

5.4 Work Unit Four

Optical Processors for Nonlinear Image Filtering During the past several years a new class of image processing operations has undergone development that allows for such things as the removal of "salt- and-pepper" noise in imagery (e.g., "snow" on a TV image) or the suppression of regular distracting features (e.g., shadows of trees that confuse a target-recognition processor looking for military vehicles in the image of a forrested area) without obliterating other critical scene detail. These operations are often referred to as "nonlinear filtering" operations. Their implementation on a computer or special-purpose digital image processor is relatively slow because of the massive computational effort required.

Researchers at Georgia Tech, with support from the Joint Services Electronics Program, are showing how such operations can be implemented rapidly using optical techniques. The key to the speed of operation is the complete parallelism of the optical methods: each and every point on an input image is operated on simultaneously. In their method the Tech researchers use a technique known as threshold decomposition to break an image up into a succession of intensity-level slices, each slice corresponding to a different brightness level of the image. Thus, bright regions of the image are processed first, in the form of small shapes, then surrounding regions that include lower brightness levels as larger shapes, and so forth.

The processing of the threshold-decomposition-produced shapes consists of a nonlinear operation that removes very fine noise-like features from the shapes but otherwise preserves their original contours. An example is shown in the figure. This operation is performed by blurring the shapes optically in a controlled way and re-imaging with a high-contrast imaging device. After the nonlinear processing resulting slices are integrated, or stacked, to produce as output a processed gray-scale image.

Research at Georgia Tech is concentrated on investigation of the optical techniques and on the development of new processing applications, including clutter rejection and target acquisition. In order for the methods to be fully competitive with digital electronic methods there must be improvements in the technology of non-scanning high-contrast opto-electronic imaging devices.

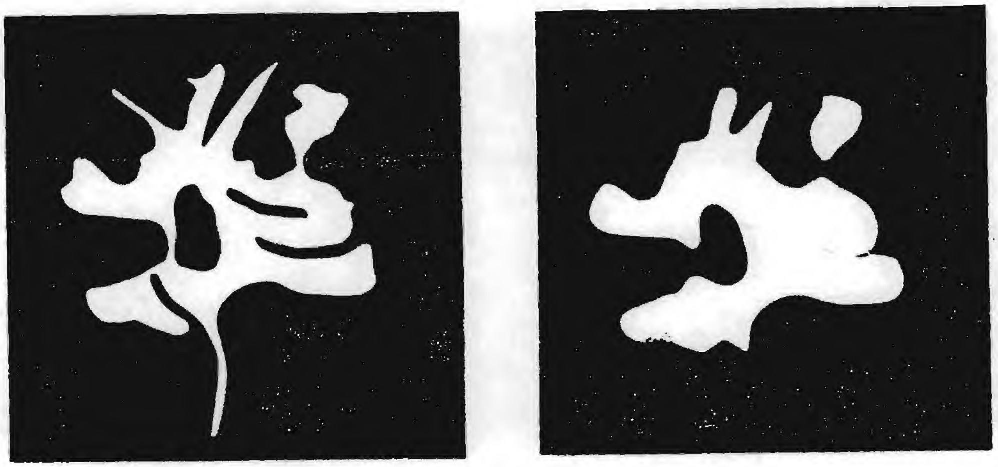

Figure 1: Example of Nonlinear Filtering: Left, original shape; right, processed shape with "lakes" and "peninsulas" removed.

5.5 Work Unit Six

In Situ Measurement of Electrical Constitutive Parameter The electrical constitutive parameters: permittivity, conductivity and permeability, must be known before Maxwell's equations can be solved in a material. These parameters are generally determined experimentally. In situations where samples of the material cannot be taken to a laboratory for measurement, as in situ measurement of the parameters may be necessary. For example, the electrical constitutive parameters of the earth are required to compute the performance of radio propagation links. The parameters of a sample of earth may change on removal due to changes in density and moisture content. As a result, an in situ measurement will provide more accurate values for these parameters.

In this work, monopole type antennas were studied as probes for the in situ measurements of the electrical constitutive parameters of materials. These probes consist of one or more cylindrical rods mounted on an image plane; one of the rods is driven by a coaxial line. The measurement techniques developed use the measured input impedance of the antenna to determine the constitutive parameters of the surrounding medium. The techniques do not make use of a theoretical analysis for a particular shape of antenna; they use only the most general analytical properties of the antenna impedance. The techniques were verified by making measurements of materials with known constitutive parameters (alcohols and saline solutions) over broad frequency ranges.

A particularly simple probe was developed for making measurements of the constitutive parameters of the earth.

5.6 Work Unit Seven

Near-Field Radar Cross Section Measurement Technique Aircraft and missile radar guidance systems operate on the premise that the target has a scattering function (radar cross section) which is independent of distance, R, except for a $(1/R)^4$ amplitude factor. This premise is correct in the "far-field" of a target, but not correct in the radiating near-field of a target. The far-field distance for a typical fighter aircraft for a radar frequency of 10 GHz is approximately two miles. Thus a radar-guided seeker, seeking such a fighter aircraft should operate correctly up to a distance of two miles from the target. Closer to the target, the seeker will experience scintillation and "glint" as the various major scatterers of the target add in and out of phase due to the increasing phase taper of the radar illumination as the seeker approaches the target. At a distance of approximately one-half mile from the target, wing tip scatterers are illuminated with a phase of 180° with respect to the illumination at the center of the target. Thus the total scattering from the target can vary rapidly with distance, causing the seeker system to generate large steering commands from which it often cannot recover. The theory and technique for the measurement of the near-field scattering of scatterers has been developed and allows a monostatic scattering measurement to be performed at a single (and small) radius from the target. The scattering at any larger radius may then be straight-forwardly calculated from the single measurement. Near-field measurements of a flat plate scatterer were measured and correctly predicted scattering at larger distances including the well-known far-field scattering of a flat plate. The theory and technique for the measurement and subsequent radius dependent calculation of the target scattering continue to be refined and documented using various classic targets.

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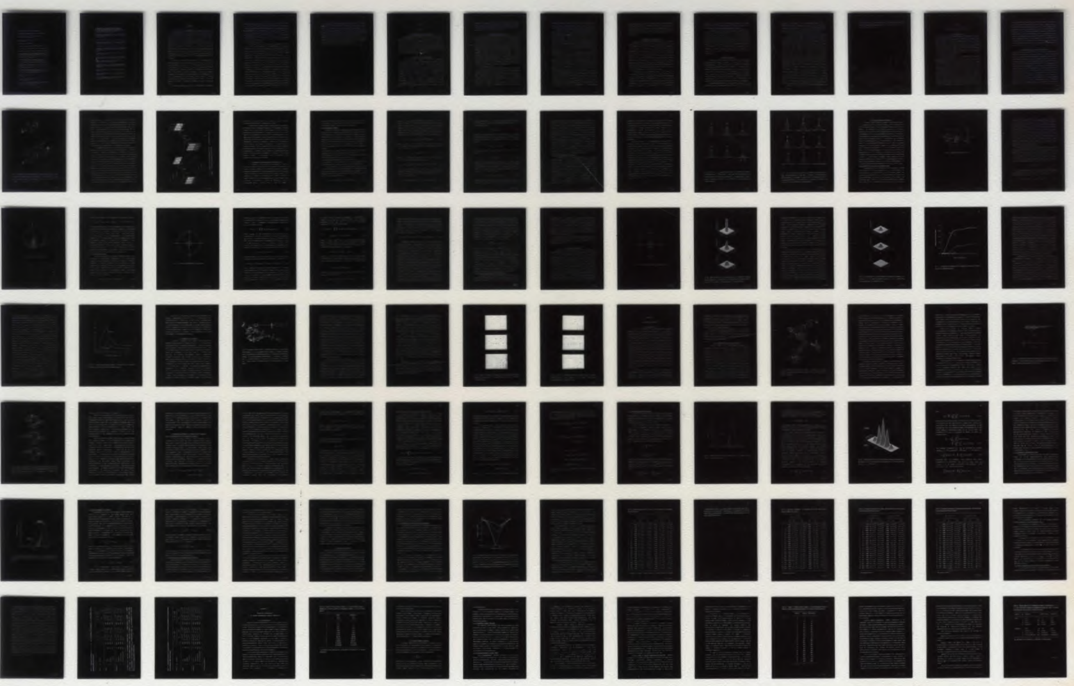

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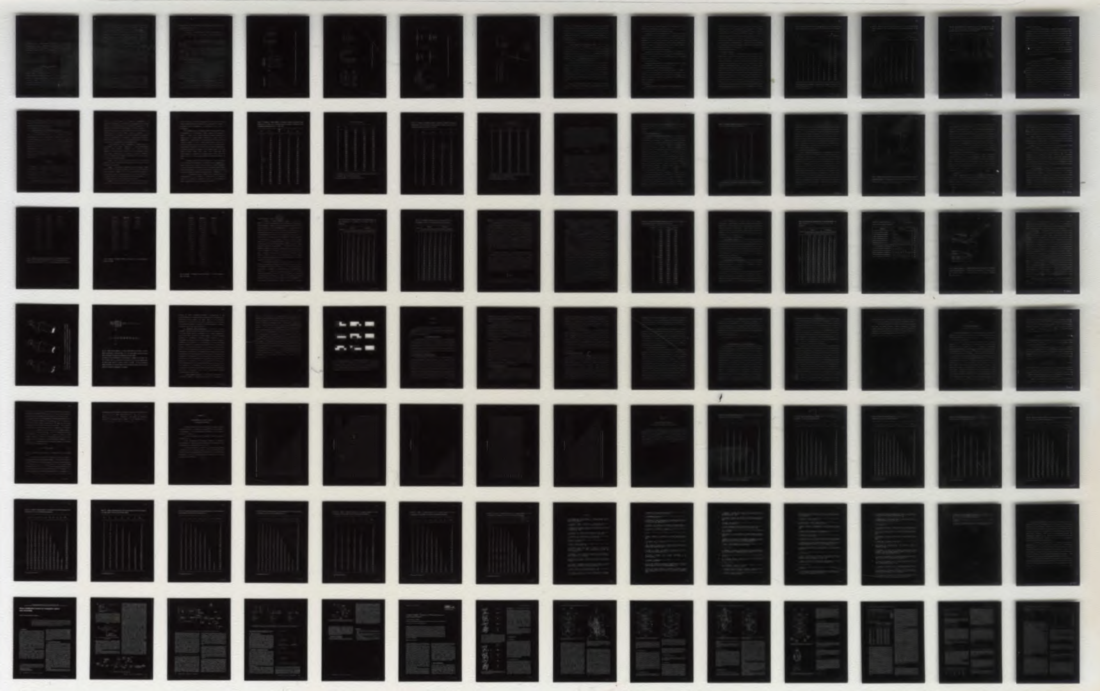

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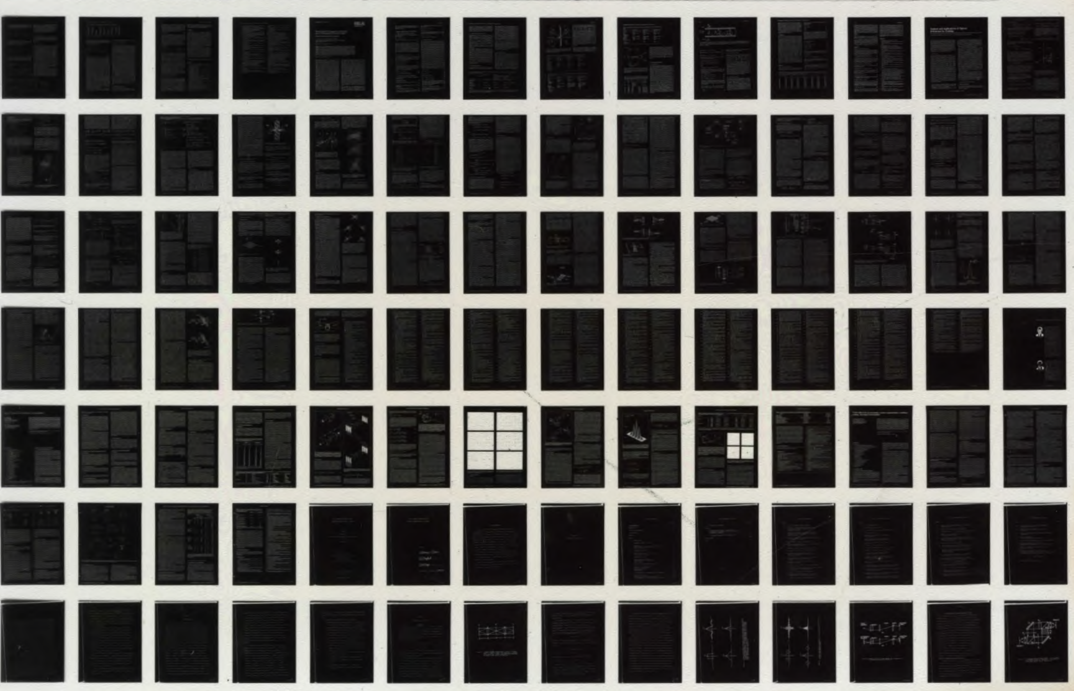

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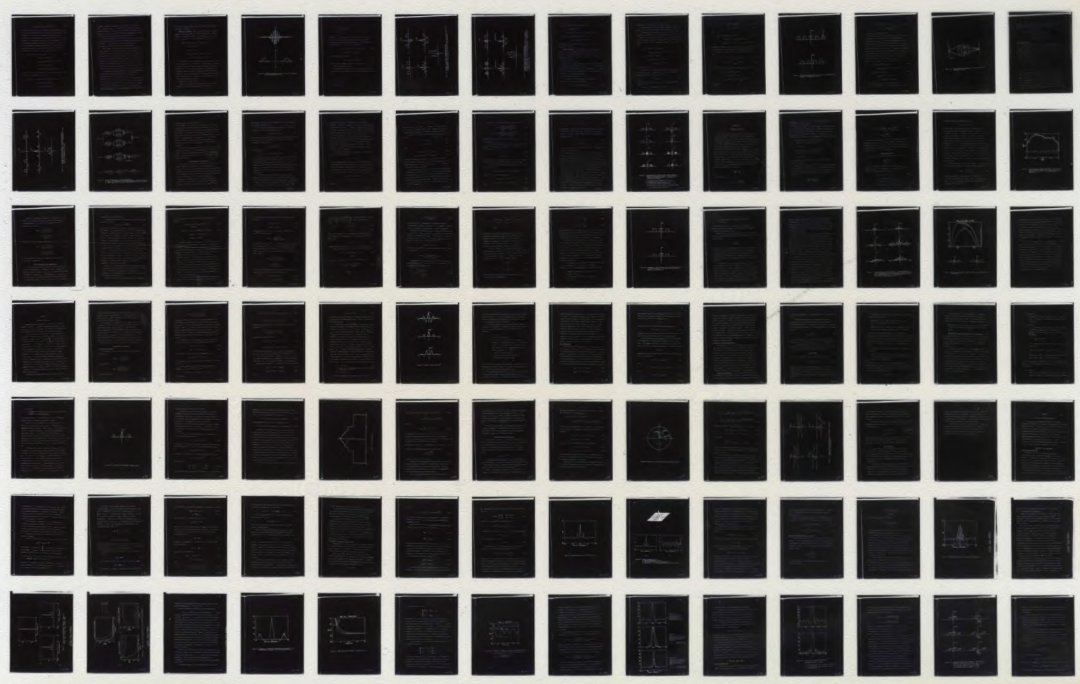

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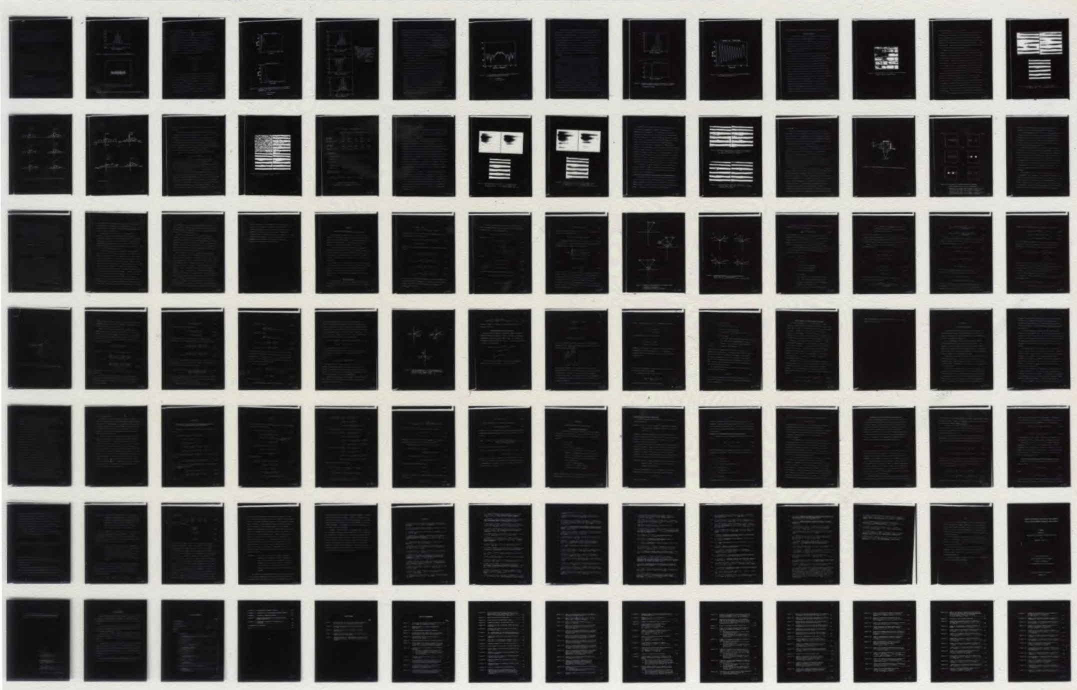

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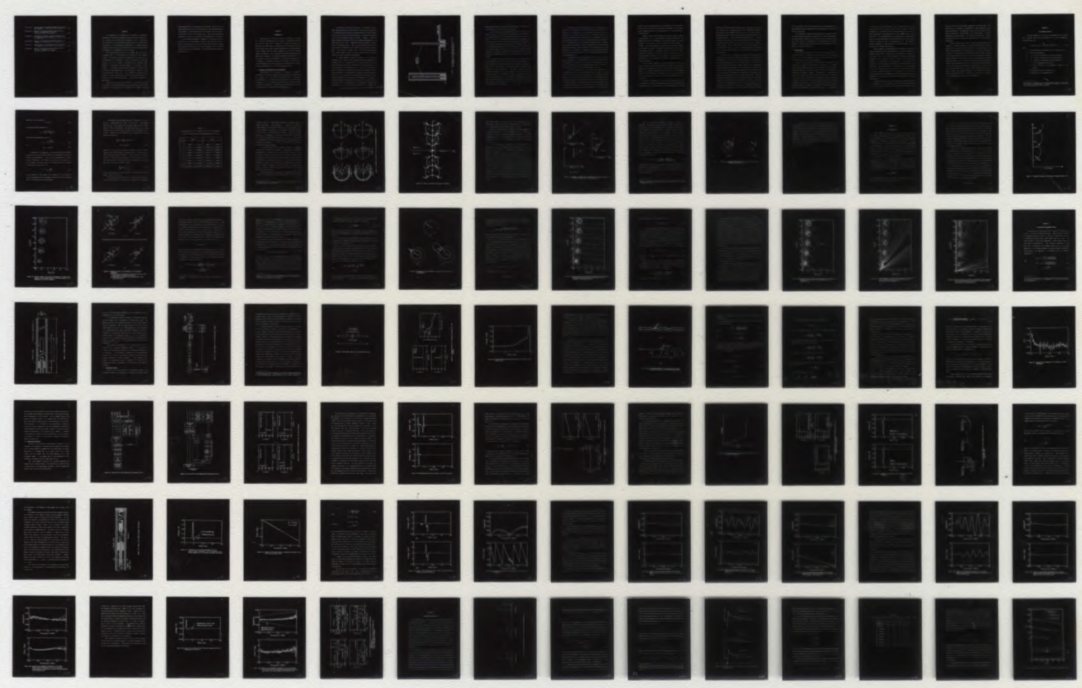

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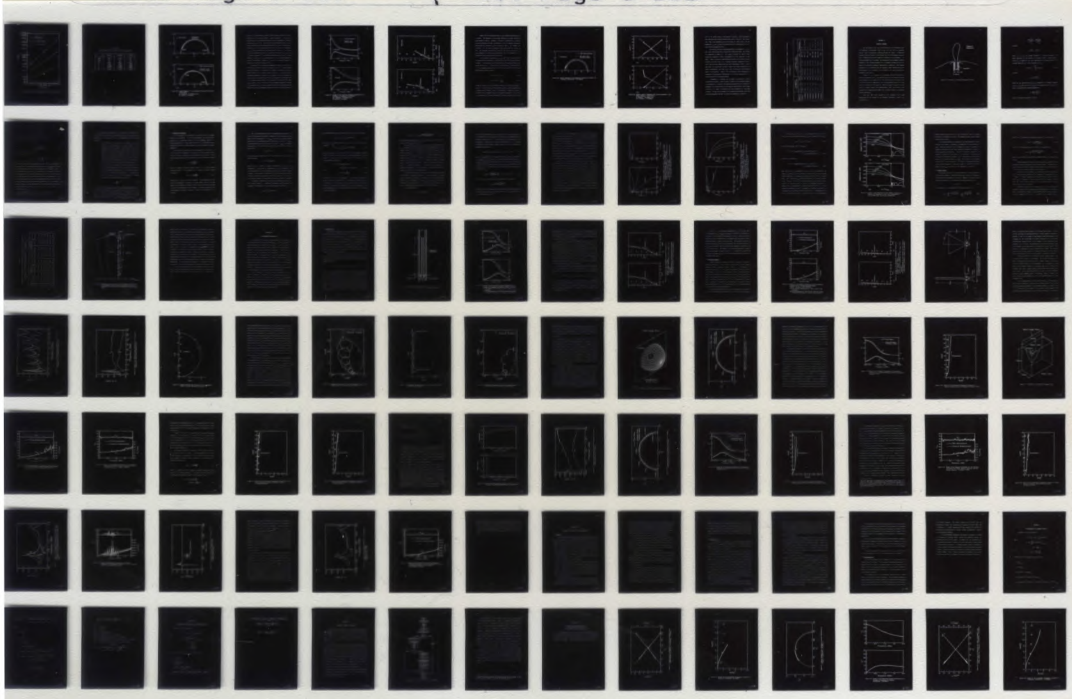

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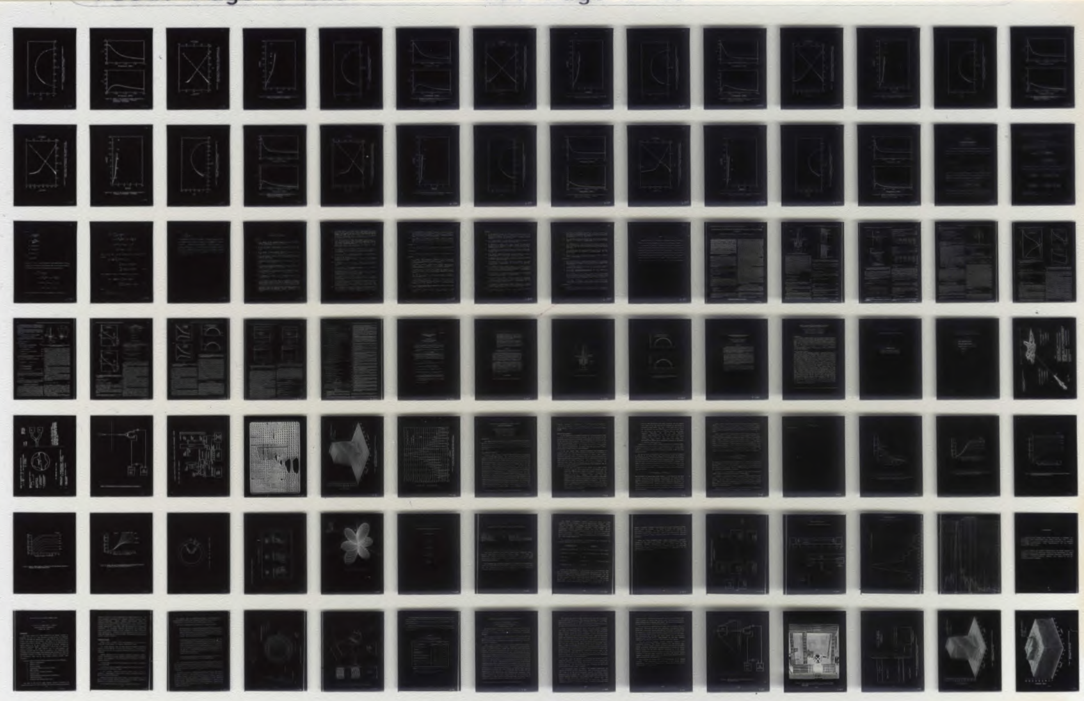

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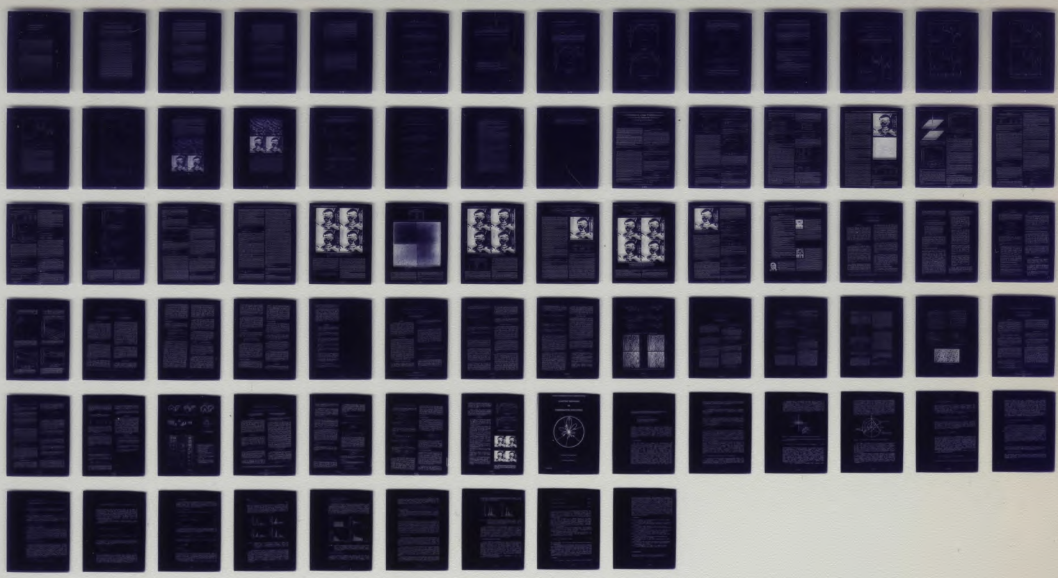

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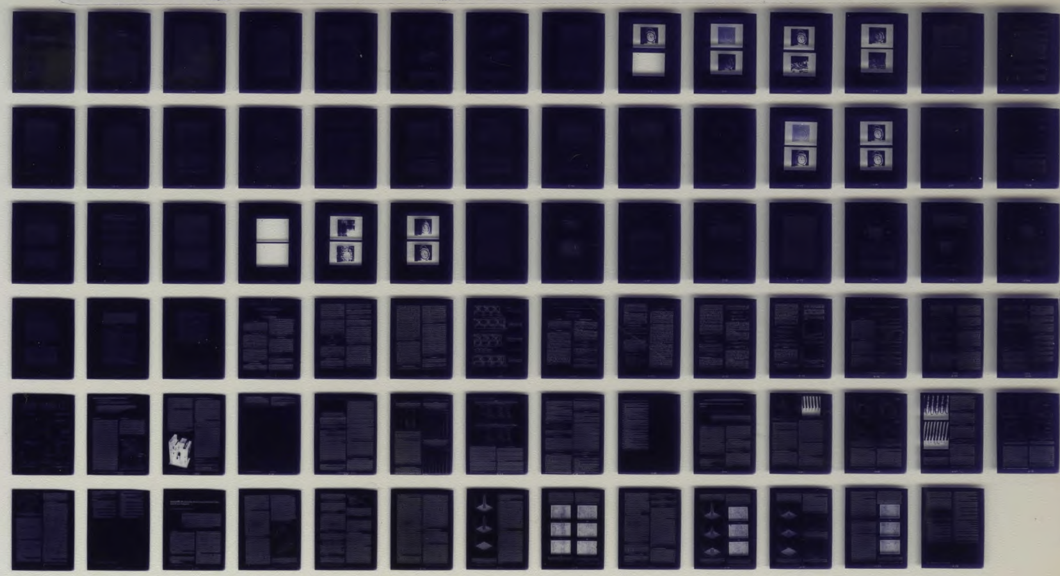

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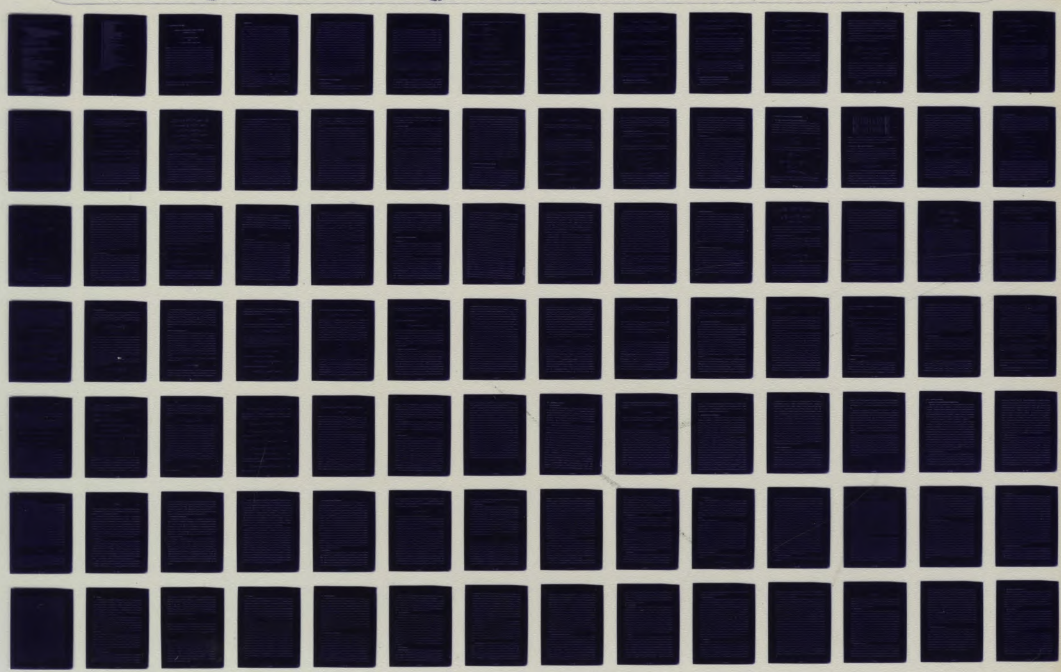

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School of E.E., GEORGIA INSTITUTE OF TECHNOLOGY
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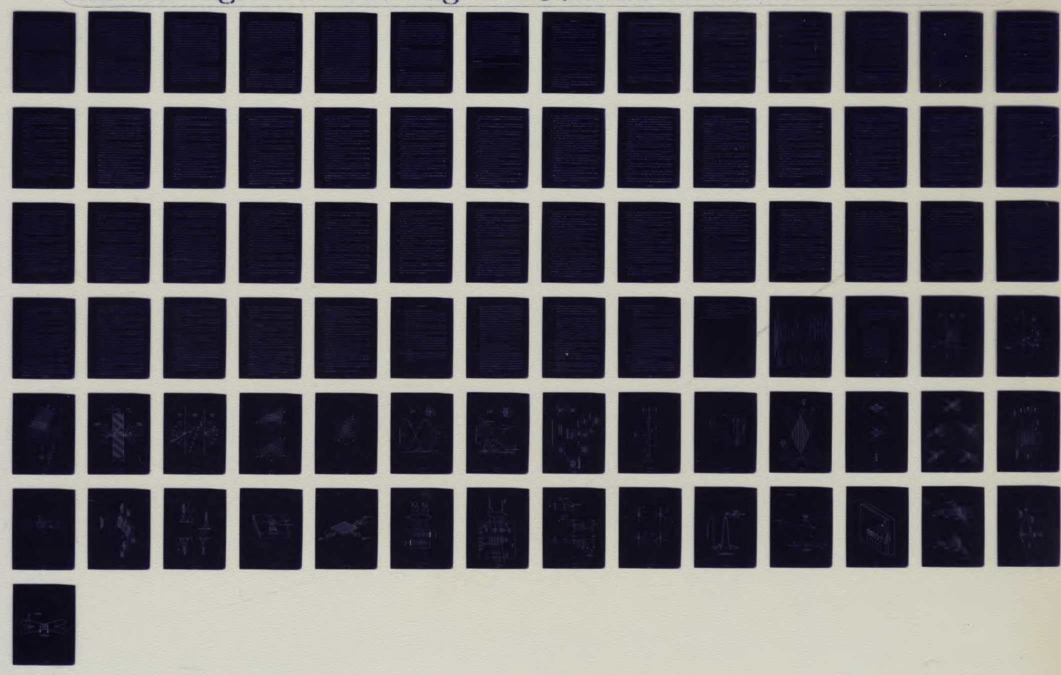

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School of E.E., GEORGIA INSTITUTE OF TECHNOLOGY
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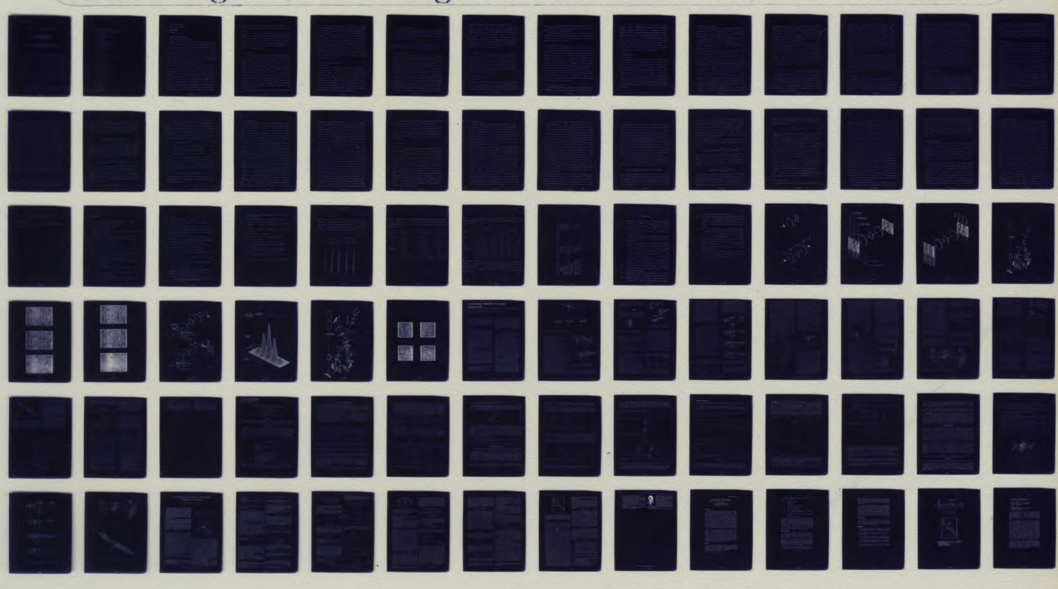

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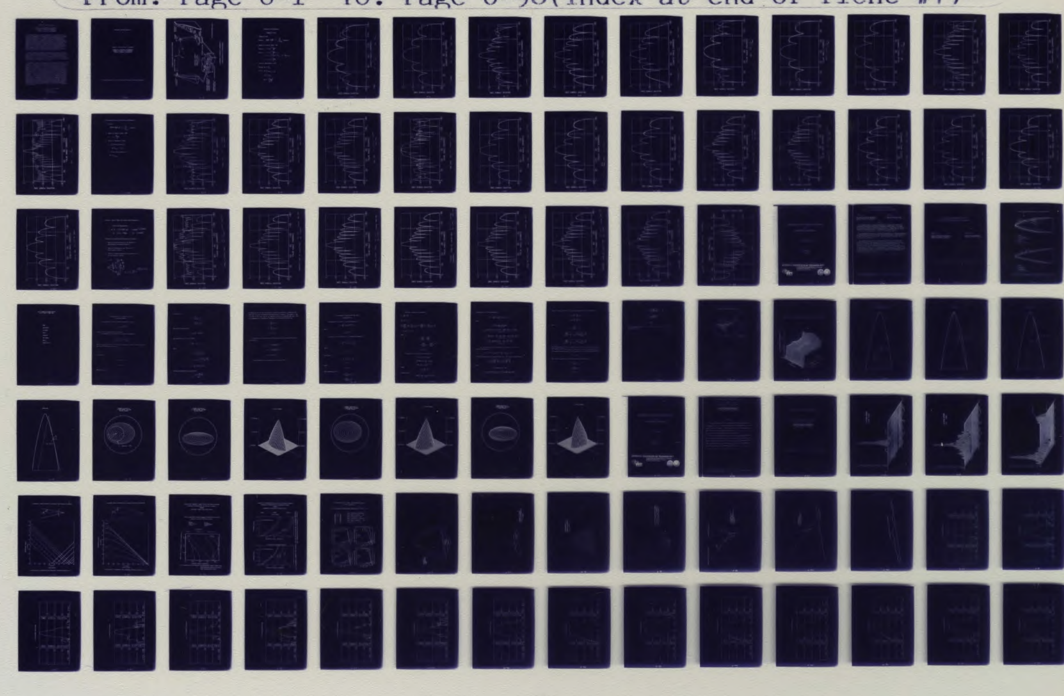

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